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S I M U L A T I O N V E R I F I C A T I O N
T E C H N I Q U E S S T U D Y

Task Report #4 (TR-4)

SIMULATION MODULE PERFORMANCE PARAMETERS AND PERFORMANCE STANDARDS

1 August 1974

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ABSTRACT

This report deals with Shuttle simulation software modules in the Environment, Crew Station, Vehicle Configuration and Vehicle Dynamics categories.

For each software module covered, this report provides a description of the module functions and operational modes, its interfaces with other modules, its stored data, inputs, performance parameters and critical performance parameters.

Reference data sources which provide standards of performance are identified for each module. Performance verification (validation) methods are also discussed briefly. Detailed treatment of performance verification techniques is deferred to a later report.

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SECTION 1

INTRODUCTION

This report covers a portion of the work done under WBS 2.0 of the Simulation Verification Techniques Study.

1.1 PURPOSE

The purpose of WBS 2.0 is to develop methods for verifying simulation fidelity with respect to the real world; i. e., to ensure that the simulator responses presented to the crew are indiscernible from those which will be experienced during actual flight. During simulator development, performance verification(validation)is performed on individual software modules, at various stages of integration, and finally for the all-up simulator system. In addition, revalidation will be necessary from time to time during a simulator's operational lifetime, as modifications are made to hardware and/or software.

WBS 2.0 is divided into three subtasks:

- WBS 2.1, Definition of Performance Parameters: Analyze each Shuttle subsystem and simulation module; define a set of parameters which completely describe each subsystem/module.
- WBS 2.2, Establishing Standards of Performance: Define methods to provide reference data to serve as standards of performance for module validation (e.g., batch programs, test data).
Define data formats, determine database impact.
- WBS 2.3, Methods for Validating Performance: Define methods for realtime performance data acquisition and comparison with reference data; define comparison criteria.

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1.2 SCOPE OF THIS REPORT

Each of these subtask efforts must be applied in the context of each subsystem/module, as well as in the context of integrated simulator system operation. Because of the considerable body of specialized information required, it is convenient to work on the performance parameter identification, reference data sources and validation methods peculiar to a module all at once, rather than dealing with different aspects of a particular module at three widely-separated times. For that reason, this report is organized on the basis of the simulation software module hierarchy, and includes module-oriented efforts which fall under all three WBS subtasks.

Figure 1-1 shows an overview of the simulation software module hierarchy developed for use in WBS 2.0. The software categories covered in this report -- Environment, Crew Station, Vehicle Configuration, and Vehicle Dynamics -- are enclosed in dotted lines.

For each module covered, this report provides a description of the module's functions and operational modes, its stored data and inputs, and its performance parameters (including "critical" performance parameters as defined below). Sources of reference (standards) data are identified, and performance-verification techniques and support software are briefly discussed.

Later reports will complete our coverage of the software module hierarchy, and deal in depth with reference data sources, data formatting, database impact, and performance verification techniques and support software.

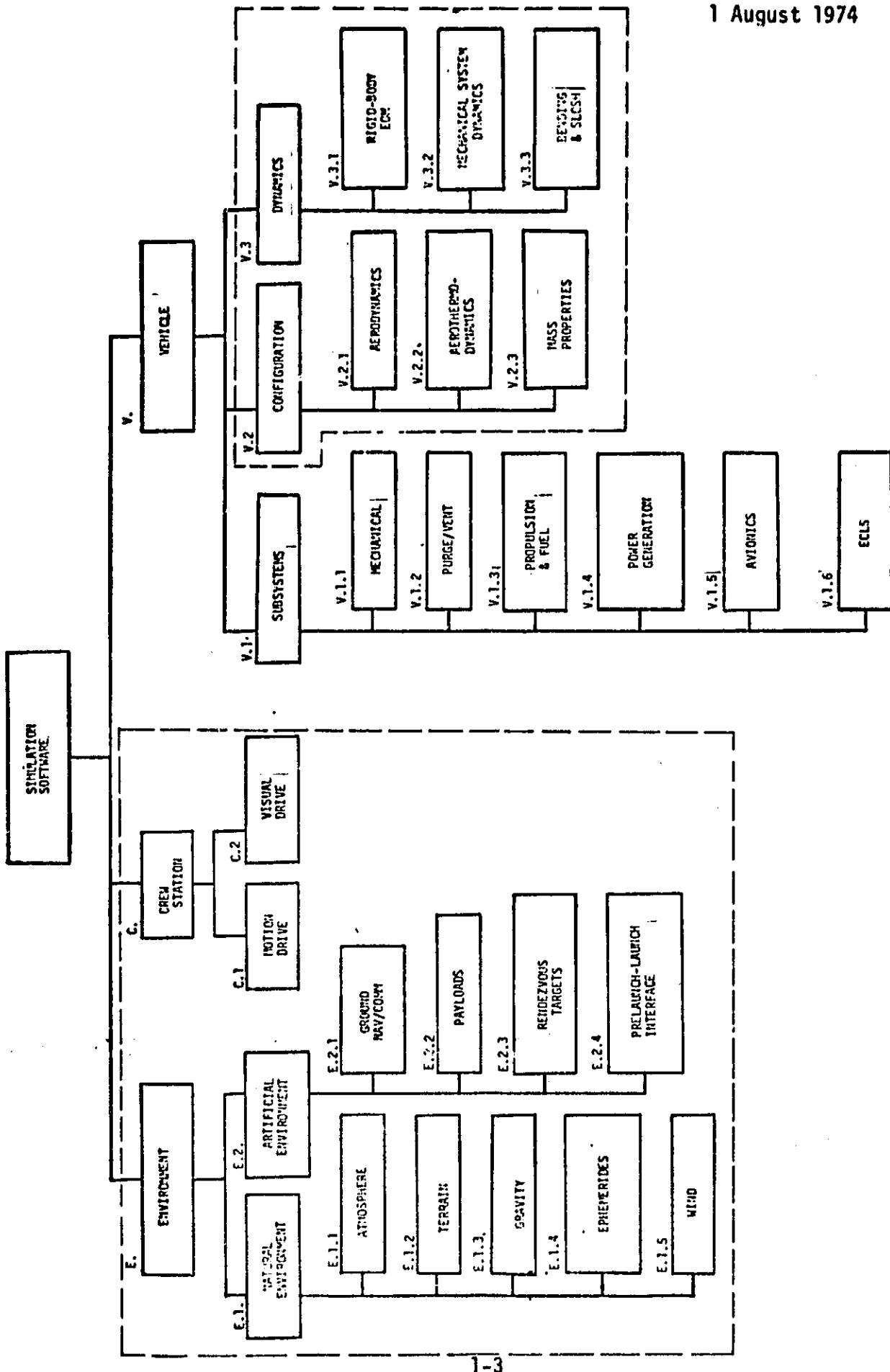


FIGURE 1-1. SUBSYSTEM/MODULE CATEGORIES COVERED IN THIS REPORT.

SECTION 2

MODULE PERFORMANCE PARAMETERS AND STANDARDS OF PERFORMANCE

2.1 GENERAL

Several topics of general applicability to all modules are treated here, to unify subsequent discussion of individual modules.

2.1.1 Performance Parameter Guidelines

In performing an analysis of each onboard subsystem and simulation software module, we must extract from the basic defining information a list of performance parameters, which completely describes the performance of the subsystem/module. By this we mean that any error or inadequacy in the simulation must show up in one or more of the designated performance parameters. We envision such a complete performance parameter list to be useful primarily in the exhaustive initial validation of the simulator.

In addition, we have further examined the complete parameter list for each module, designating a subset thereof as "critical" performance parameters. The primary utility of the critical parameter list would be in revalidating simulation modules after modifications or updates, the presumption being that, if a module's critical parameters provide acceptable fidelity, it will not be necessary to check the rest of the performance parameters. Criteria for identification of performance parameters and critical performance parameters are given below.

2.1.1.1 Performance Parameters

The performance parameters for any onboard subsystem (simulation module) or for the total system (total simulation) must have the following properties:

- a. They must be real-world variables (either continuous or discrete). Thus, synthetic variables which are defined for analysis and programming purposes -- e.g., auxiliary angles, counters, initialization flags -- cannot be performance parameters.
- b. They must be time-variable quantities, not constants; e.g., aerodynamic-coefficient tables are not performance parameters.
- c. All system "state variables" are performance parameters. (State

variables may be defined as the dependent variables in the system differential equations, when the equations have been reduced to first order).

- d. Some outputs of a module may not be performance parameters. Outputs unrelated to the module's designated functions (e.g., power consumed and heat dissipated by an IMU) are "incidental outputs", not performance parameters.
- e. Some performance parameters of a module may not be outputs. Internal variables (either continuous or discrete) not normally output from a module will still be performance parameters, if they are real-world variables, and are essential to the representation of the performance parameters which are outputs.
- f. Every variable available to a flight computer or telemetered for ground-controller use must be a performance parameter of some module.
- g. Inputs to a module are never performance parameters for that module. (This rule prevents double-counting; thus no variable will ever be a performance parameter for more than one module.)

2.1.1.2 Critical Performance Parameters

Guidelines for selection of a subset of critical performance from the set of performance parameters of a module appear somewhat less clear-cut than those for initial selection of performance parameters. A performance parameter may be denoted as a critical performance parameter for one or more of the following reasons:

- a. It is a particularly significant indicator of simulation validity for its associated module.
- b. Its accuracy has a long-term or cumulative impact upon the simulation validity; e.g., orbital drag forces, consumables expenditure rates.
- c. It is readily available to the crew (by permanent or callable display), and plays a key role in crew operational procedures.
- d. It is communicated to the flight computer(s) and plays a key

role in computer control of vehicle systems.

2.1.2 Alternate Reference-Data Sources

The Standards of Performance sought in WBS 2.2 are sources of reference data representing the real world, against which the simulation fidelity is to be evaluated. Four basic classes of reference-data source have been identified in this study:

- o Closed-form solutions: exact or approximate formulas giving answers to be compared to the output of simulation routines.
- o Independent math models: parallel software development for the explicit purpose of providing reference data for module validation.
- o Existing analysis/simulation programs: established, previously-validated programs which can be exercised with check-case data to provide outputs directly comparable to simulation module outputs.
- o Test data: vehicle and/or subsystem data from an actual laboratory or flight environment.

Table 2-1 briefly lists advantages and disadvantages of each of the four basic classes of reference-data source. These considerations will be discussed in greater detail in a later report.

2.1.3 Verification Techniques and Support Software

Figure 2-1 depicts a support-software organization suitable for the generation, handling, comparison and display of simulation and reference data required to perform simulation software validation. A complete validation software system will consist of a basic "driver" or executive (denoted SOFCHK in the figure) and a set of service routines, briefly identified in Table 2-2.

These routines will, of course, vary in degree of generality. Routines GENPT, SIMMOD, and CHKMOD must be completely "customized" for each simulator module being validated. Routine DREAD will be a data-driven

TABLE 2-1. ALTERNATE DATA SOURCES: PROS & CONS

DATA SOURCE	ADVANTAGES	DISADVANTAGES
Closed-Form Solutions	Simplicity Accuracy	Feasibility Scope
Independent Math Models	Scope Compatibility Control	Workload
Existing Analysis/Simulation Programs	Scope	Availability Documentation Incompatibility
Test Data	Fidelity	Timeliness Availability Scope Incompatibility Documentation

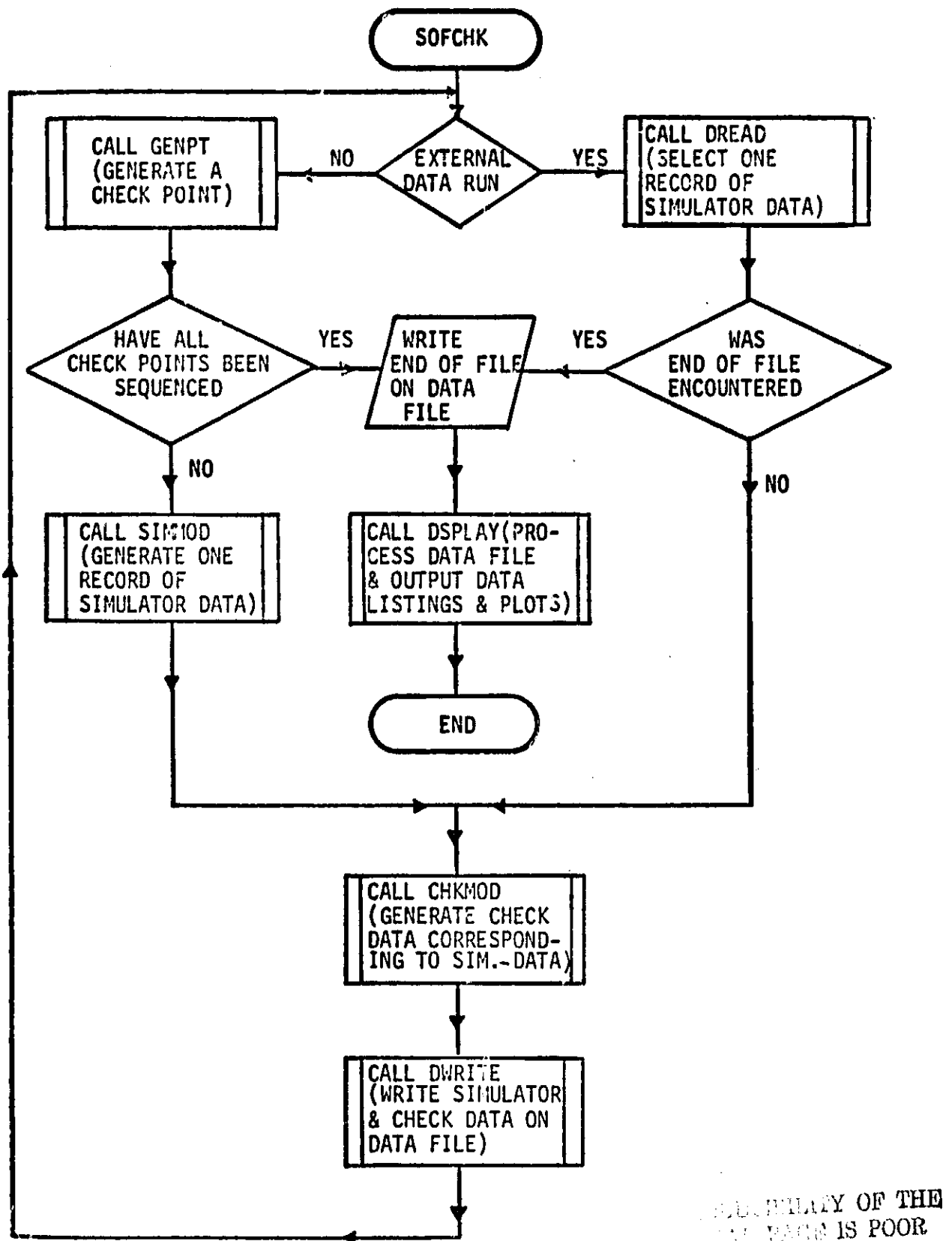


FIGURE 2-1. VALIDATION SOFTWARE OVERALL FLOW

TABLE 2-2. VALIDATION SUBROUTINES^a

SUBROUTINE	PURPOSE
DREAD	Reads records from a data tape or disc file generated during a simulator performance run; selects data for the appropriate module and places it into a data array.
GENPT	Generates a checkpoint which includes all data required for input into the module to be verified.
SIMMOD	Interfaces with the simulation software module and places the input and output data into a data array.
CHKMOD	Interfaces the "reference" software module and places the input and output data into a data array compatible with the simulation software data array.
DWRITE	Writes the data from the simulator software module and the reference module onto a data file to be used for comparison processing.
DSPLAY	Processes the data file written by DWRITE. Performs automated comparisons of simulation and reference data, and/or generates listings and plots for manual comparison of data. Incorporates a variety of differencing techniques and comparison criteria.

^aMath flows and comprehensive discussions of these routines will be provided in a later report.

input routine, designed to be compatible with the basic data-output structure of the simulator being validated. Finally, routines DWRITE and DSPLAY should be highly independent of the characteristics of the module being validated. The greater the degree of generality designed into the support software, of course, the less specialized coding and setup required to validate each individual module.

Subsequent sections of this report describe some of the customized modules required to support validation of individual simulation modules. Designs for the validation executive and the generalized support routines will be presented in later reports.

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2.2 ENVIRONMENT MODULES

Environmental conditions external to the Orbiter vehicle interface with and influence the performance of the Shuttle systems and/or vehicle. These environments can be divided into two basic divisions, natural and artificial. The natural environment includes those conditions which occur in nature. The artificial environment includes the man-made or artificially created conditions. These two groups are discussed in this section.

2.2.1 Natural Environment

Several natural factors influence the Orbiter vehicle performance, dynamics, and navigation. This section identifies these natural factors, section module functions, and parameters related to the module, and suggests a technique for verification of the module.

2.2.1.1 System Description

The natural factors influencing vehicle performance are atmosphere, wind, gravitation potential, sun/moon/star ephemeris, and terrain elevation. The atmosphere and wind impact the Orbiter aerodynamically, producing forces and moments. The trajectory of the vehicle is influenced by the gravitational potential. The locations of the sun, moon, and stars provide guidance and navigation inputs. The terrain near the landing site reflects the radar altimeter signals for altitude measurement during the final approach and landing maneuvers.

2.2.1.2 Module Functions and Parameters

The Natural Environment Module provides the inputs required to simulate their influences. Figure 2-2 provides a possible module configuration and interfaces with the other modules. Table 2-3 gives the list of parameters associated with the module. The functional elements within the module are described below.

Atmosphere and Wind

The atmosphere and wind element provides the following functions:

- Dynamic pressure - a function of density and relative velocity of the Orbiter and air stream.
- Mach number - a function of air temperature, air velocity, and vehicle velocity.

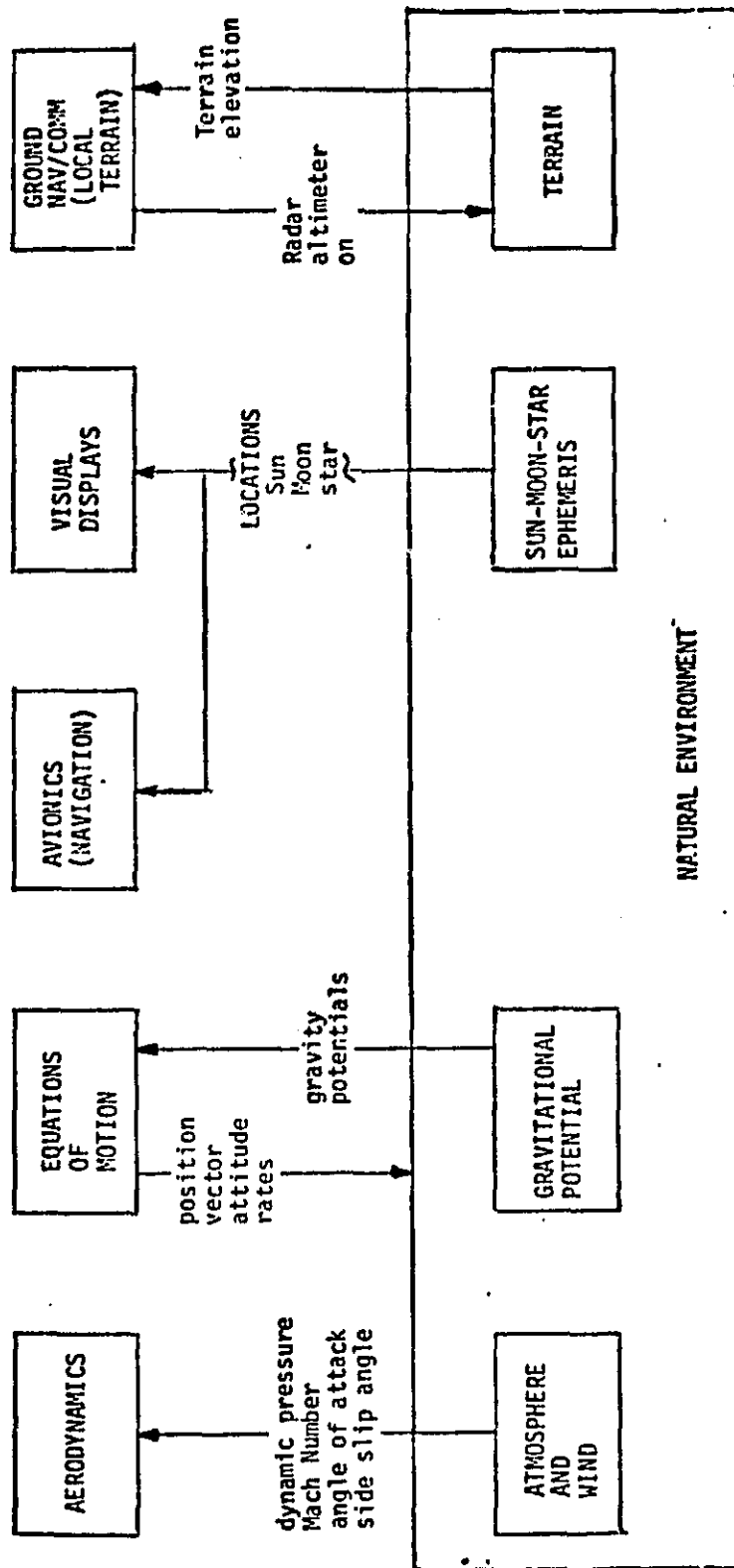


FIGURE 2-2 . NATURAL ENVIRONMENT MODULE, FUNCTIONAL ELEMENTS, AND INTERFACES

TABLE 2-3 . NATURAL ENVIRONMENT MODULE PARAMETERS

SYMBOL	PARAMETER	TYPE ^a
T	Universal Time	I
r	Vehicle Position vector magnitude	I
ϕ	Vehicle Position Latitude	I
θ	Vehicle Position Longitude	I
\underline{R}	Inertial Position Vector	I
\underline{R}_e	Earth fixed position vector	I
-	vehicle attitude, rates	I
h	Vehicle geometric altitude	I
a	Vehicle geopotential altitude	I
-	Locations (sun, moon, stars)	CP
\underline{G}	Earth gravitational acceleration vector	CP
\underline{S}	Sun line-of-sight vector	CP
\underline{M}	Moon vector	CP
q	Dynamic Pressure	CP
M	Mach number	CP
α	Angle of attack	CP
β	Side slip angle	CP
ρ	Atmospheric density	P
P	Atmospheric pressure	P
-	Atmospheric Temperature	P
V_s	Speed of sound	CP
\underline{V}_w	Wind Velocity	P
e_T	Terrain elevation	CP

^aLegend = I = Input

P = Performance Parameters

CP= Critical Performance Parameters

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- Angle of attack/side slip angle - functions of air velocities, Orbiter velocity, and Orbiter attitude.

Gravitational Potential

This element provides the force, due to the earth mass, acting on the vehicle. This force is a function of the mass, distance, location of the vehicle, and includes the zonals, sectorals, and tesserals harmonic terms.

Sun/Moon/Star Ephemeris

The ephemeris provides the position of the sun, moon, and stars as a function of time.

Terrain

The elevation of the local landing terrain as a function of vehicle position is provided by this element.

2.2.1.3 Module Verification

The comparison method described in Sect. 2.1.3 is particularly applicable for verification of the simulator environment model because most of the software models required to verify the environment are available for the reference module. Verified software representing the potential and atmosphere models is available from the digital programs described in References 1, 2, and 3. Reference 1 also documents an ephemeris routine which can be used to verify computation of the Sun and Moon vectors. In applying the method to the environment the functions performed by GENPT and CHKMOD (Figure 2-1) must be defined.

To verify the environment model, position vectors and time points must be generated to sequence all logic paths of the potential model, atmosphere model, terrain model, ephemeris model, and wind model. Assume GENPT calls a routine GENRT (Figure 2-3) to provide these check points. By making the altitude and time increments small enough all loops will be sequenced.

ENVIOR (Figure 2-4) represents a typical environment model to be called by the routine CHKMOD. The input to ENVIOR is a position vector, R , and a Universal Time, T , which are generated in GENRT or read from a performance run. The parameters which are to be verified are presented in Table 2-3. These parameters are placed in the data array for comparison processing.

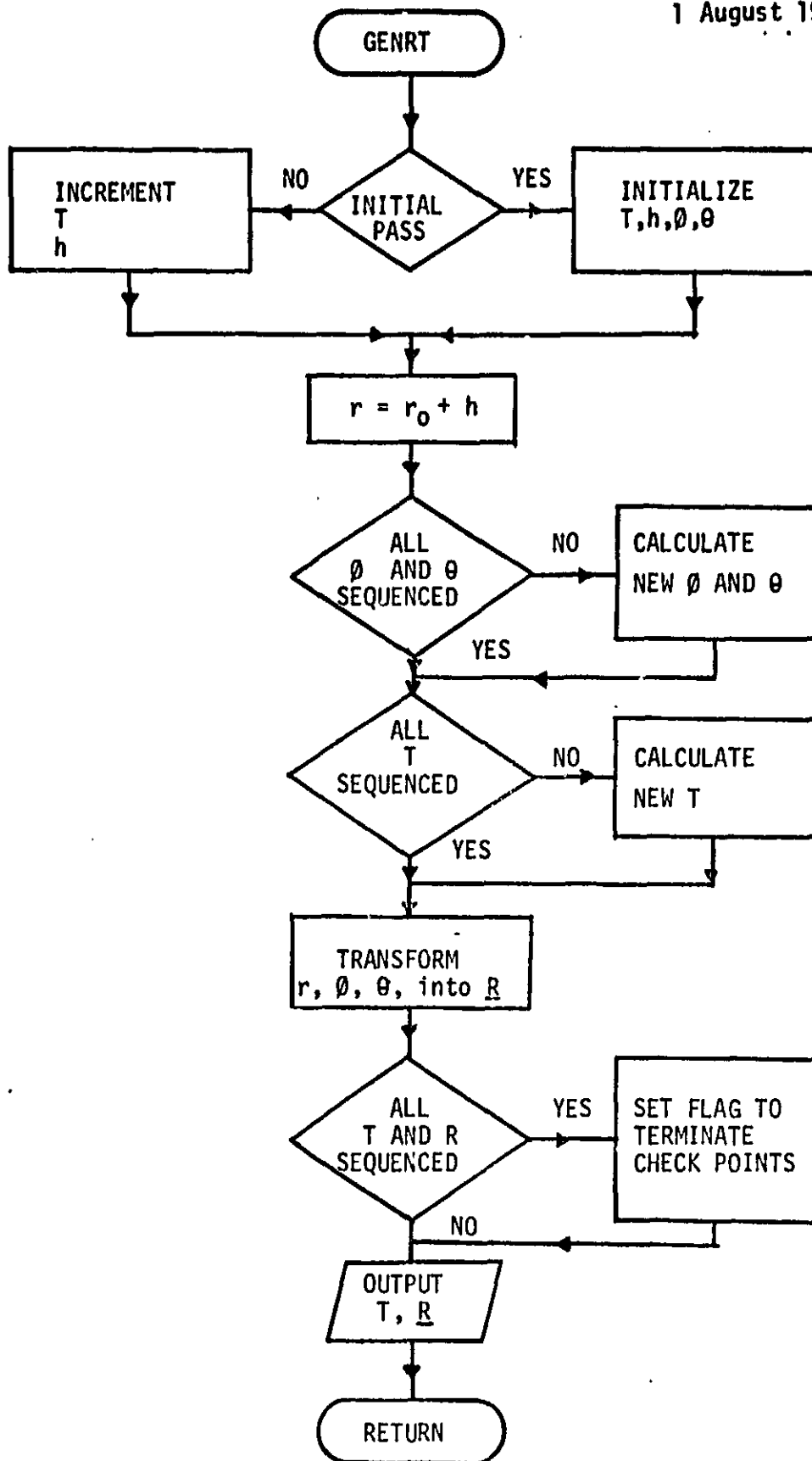


FIGURE 2-3. GENRT FLOW CHART

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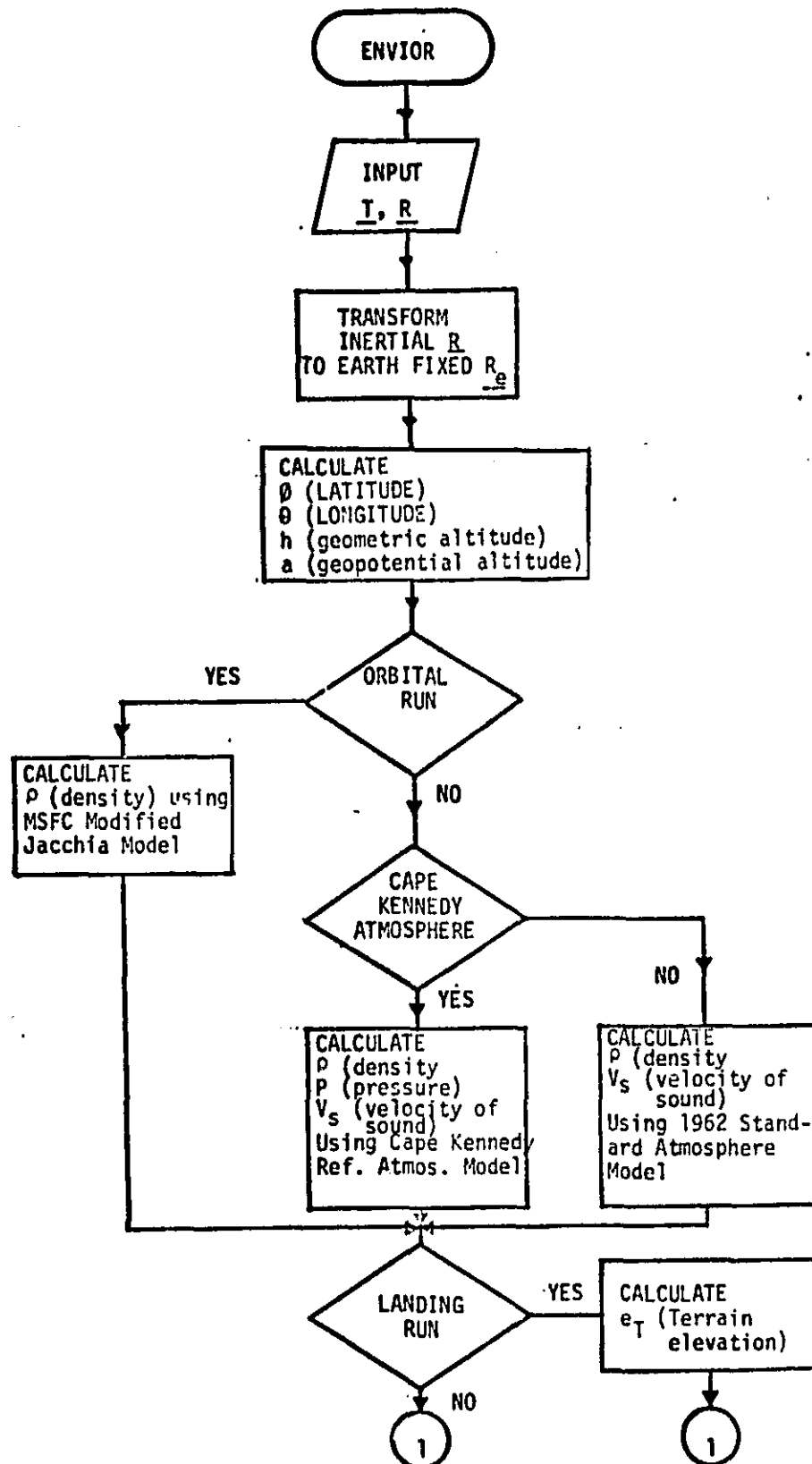


FIGURE 2-4. ENVIOR FLOW CHART

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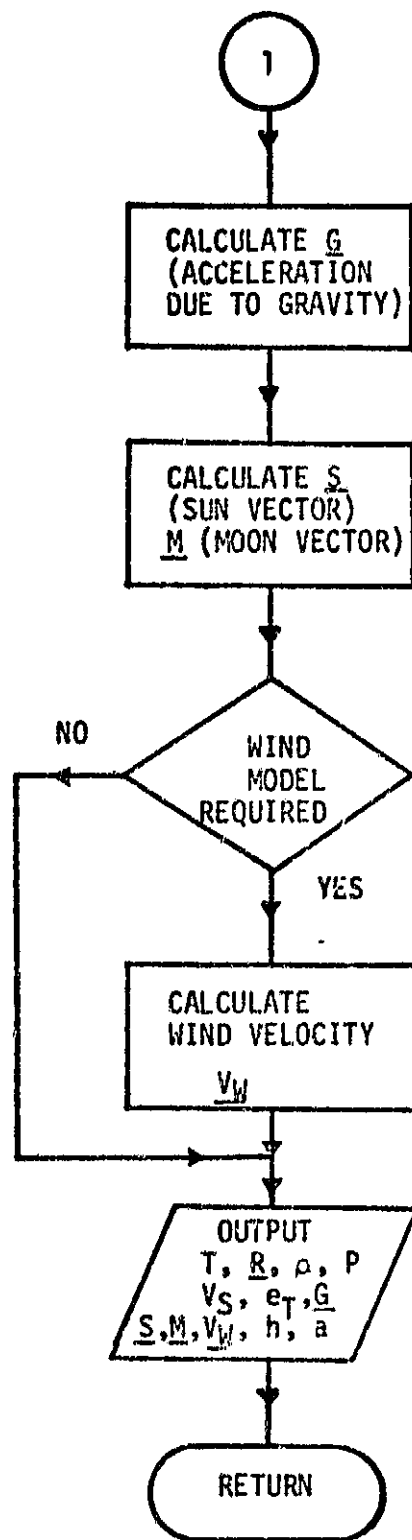


FIGURE 2-4. (continued)

Relative to Figure 2-4, the transformation from an inertial frame to an earth fixed frame is discussed in Reference 4 and the atmosphere, potential, and Ephemeris models necessary to compute density, pressure, speed of sound, gravitation acceleration, and the sun and moon vectors are discussed in Reference 5 .

The software required to verify these models is available in a variety of analysis programs. However, the terrain and wind models are dependent on the type of mission being simulated and the accuracy required. For example, the wind model could represent a nominal wind with random turbulence added using a filter for nominal runs, or the wind model could represent extremes and be used for engineering test runs. Models for the wind and terrain have been implemented on the MDAC Shuttle Mission Engineering Simulator in St. Louis and software for these models is available. The models and typical results are documented in Reference 6. However, detailed, user-oriented documentation is not presently available. In any case, care should be taken to assure that the reference software for the winds and terrain represent the same model as the simulator model.

2.2.2 Artificial Environment

Several artificial environments exist which interface with the Orbiter vehicle. These environments include:

- Ground Navigation/Communications
- Payloads and Rendezvous Targets
- Prelaunch/Launch Interface

These three modules are discussed in this section.

2.2.2.1 Ground Navigation/Communications

Various radio frequency interfaces between the Orbiter and the ground provide Navigation and Communications capabilities. This section provides a description of a representative Space Shuttle Ground Navigation/Communications subsystem, identifies the Ground Navigation/Communications module interfaces with other modules, identifies the parameters and functions associated with the module, and provides a flowchart technique for performing the verification of the module. The detail is general, but is appropriate for the purpose of the techniques study.

System Description

The ground navigation/communications network provides the radio frequency communication interface to the Shuttle Orbiter navigation/communications subsystem. Review of the Orbiter Nav/Comm subsystem indicates the following ground system capabilities are required.

- Dual antenna S-band telemetry reception.
- UHF "voice" reception and uplink.
- STDN/TDRS transponder reception and uplink.
- SGLS transponder reception and uplink.
- Radio Frequency Navigation Aids uplink.

These interfaces are provided by various combinations of ground based and satellite equipment, primarily antennas receivers, and transmitters. The one exception to this is the radar altimeter which depends on the ground reflection of the Shuttle transmitted signal for proper operation. The performance characteristics of the primary equipment and the site (and satellite) location determine the proper operation of the navigation/communication system.

The equipment characteristics of major concern are those of the receivers, transmitters, and antennas. The receivers have two primary characteristics of interest, tuned frequency and output power. The antenna characteristics are frequency band, gain and gain pattern. Secondary antenna pattern affects are caused by antenna gimbal drive limits and local terrain interference, causing the site coverage

capability to vary with azimuth and elevation angle of line-of-sight to the shuttle.

Module Functions and Parameters

Figure 2-5 provides an overview of the Navigation/Communications Ground Station Module functional elements and interfaces with other modules. There are basically five functions performed within the module. These functions are to determine proper conditions, signal strengths received, and signal strengths radiated, locations, etc. for each of the following communication or navigation subsystems.

- . Dual S-band telemetry reception.
- . UHF voice communications.
- . STDN/TDRS transponder communications.
- . SGLS transponder communications.
- . Navigation Aids uplinks.

Table 2-4 provides a listing of the parameters associated with the Module and the designation of parameter type. Section 2.1.1 provides the criteria used in determining the parameter type. The functions performed by each element and the factors involved in calculations are as follows.

Dual S-Band Telemetry Reception Element - The Dual S-Band element performs the following functions for the reception of Shuttle FM transmitter, TLM transmitter, and DFI transmitter data.

- Make proper station (Ground) selection-function of station location, capabilities, and vehicle location, transmission frequency, etc.
- Determine adequate received signal strength-function of vehicle attitude, range, antenna gain pattern, radiated signal level; ground station location, tracking antenna gain pattern (azimuth, elevation angle), receiver sensitivity, vehicle transmitted signal.
- Enable/disable reception of proper telemetry downlink with appropriate noise level, etc.

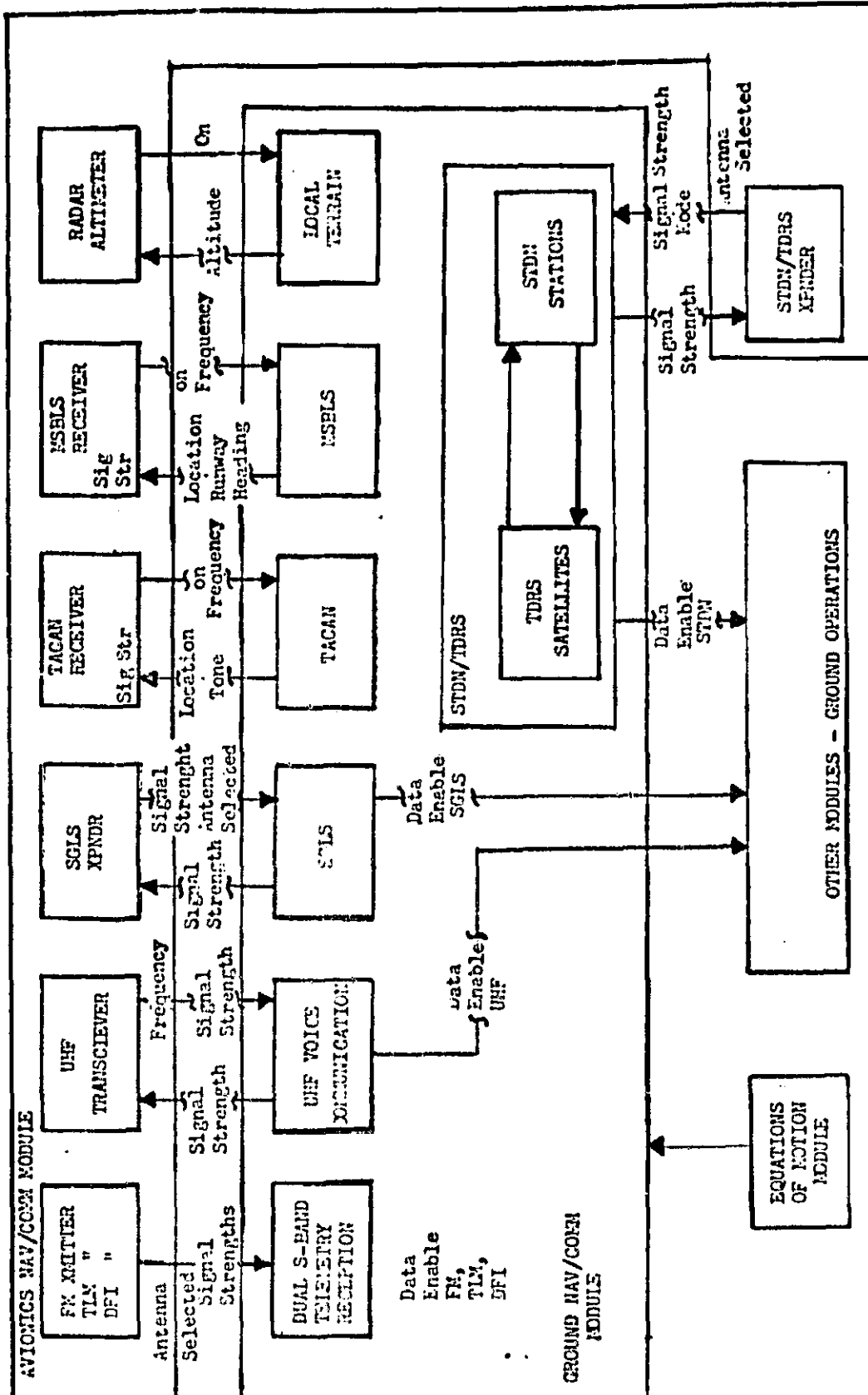


FIGURE 2-5. GROUND NAV/COMM MODULE, FUNCTIONAL ELEMENTS, AND MODULE INTERFACES

Table 2-4. GROUND NAV/COMM SUBSYSTEM PARAMETERS.

Parameter	Type ^a
Shuttle vehicle position, attitude, velocity	I
Shuttle antenna selection tags (Dual and Quad S-Band)	I
Shuttle transmitter active flags (FM, TLM, DFI, UHF, STDN, SGLS)	I
Shuttle selected channel (frequency) tags (MSBLS, TACAN, UHF)	I
Shuttle selected STDN/TDRS transmission mode tag	I
Shuttle Receiver active flags (TACAN, MSBLS)	I
Shuttle Radar Altimeter flag	I
Ground station inhibit flags	I
Shuttle/station Line-of-sight contact flags (UHF, STDN/TDRS, SGLS, TACAN, MSBLS)	CP
Ground station selection tags (FM, TLM, DFI, UHF, STDN, SGLS, TACAN, MSBLS)	P
Ground station reception enabled flags (FM, TLM, DFI, STDN/TDRS, SGLS, UHF)	CP
Ground Station antenna tracking angles	CP
Ground Station position coordinate (FM, TLM, DFI, STDN/TDRS, SGLS, UHF, TACAN, MSBLS)	P
Shuttle/Ground station Range	CP
Ground station received signal strengths (FM, TLM, DFI, STDN/TDRS, SGLS, UHF,)	CP
Code identification and tone enable (TACAN, MSBLS)	CP
Ground selected station frequency (TACAN, MSBLS, UHF)	P
Local Terrain Altitude	CP

^aLegend: P = Performance Parameter
 CP = Critical Performance Parameter
 I = Input Parameter

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UHF Voice Communications Element - The UHF voice communications element functions are the same as the Dual S-Band Telemetry Reception Element except that the data enabled is downlink voice, and the following addition:

- Calculate and output the ground transmitted signal strength- a function of transmitter power, antenna gain patterns, range, elevation angle, azimuth, atmospheric attenuation, etc.

STDN/TDRS Element - The STDN/TDRS Element performs the following functions:

- Make proper ground station selection-function of station location capabilities; vehicle location, satellite position, etc.
- Determine adequate received signal strengths-function of vehicle transmitted signal strength, antenna selected, antenna gain pattern (azimuth and elevation angle), receiver sensitivities, mode selected, satellite position, etc.
- Enable/disable data reception.
- Determine and output transmitted signal strength-function of transmitters power, antenna gain patterns, range, elevation angles, azimuth, etc.
- Determine Doppler-function of ranges, range rate etc.

SGLS Element - The SGLS functions are the same as the STDN/TDRS element except for the SGLS frequency, no TDRS, and different ground station locations, etc.

Navigation Aids Element - This element provides for TACAN and MSBLS transmissions and local terrain altitude.

- TACAN functions:

Make proper ground stations selection-function of selected frequency, vehicle location, etc.

Determine ground transmitted signal strength-function of transmitter power, antenna gain pattern, vehicle elevation angle, azimuth, etc.

Output station identification tone enable, station frequency, station location, and transmitted signal strength.

- MSBLS functions:

Make proper stations selections-function of vehicle location, selected frequency, etc.

Determine ground transmitted signal strength-function of transmitter power, antenna gain pattern, vehicle location, etc.

Output station identification code enable, station location, run way heading, transmitted signal strength, frequency, etc.

- Local Terrain functions:

Determine local terrain altitude-function of vehicle location, azimuth, radar altimeter on/off, etc.

Output altitude of terrain.

Module Verification

The verification technique presented in section 2.1.3 can be used for verification of the Ground Navigation/Communications module. Figure 2-1 provides the basic flow chart for the technique. The subroutine "CHKMOD" in Figure 2-1 is provided by the validator and represents a software model, test results, analysis results, etc. selected by the parameter values determined by the subroutine "GENPT". Figures 2-7 thru 2-12 provide the drivers necessary to complete "GENPT". Figure 2-6 provides the determination of completion of all desired checkpoints. The proper use of this or a similar technique and proper selection of various driver conditions will provide a thorough verification of the simulation module and related data files for station locations, equipment, etc. Each "check point", accuracy, and reference data are under the control and selection of the validator.

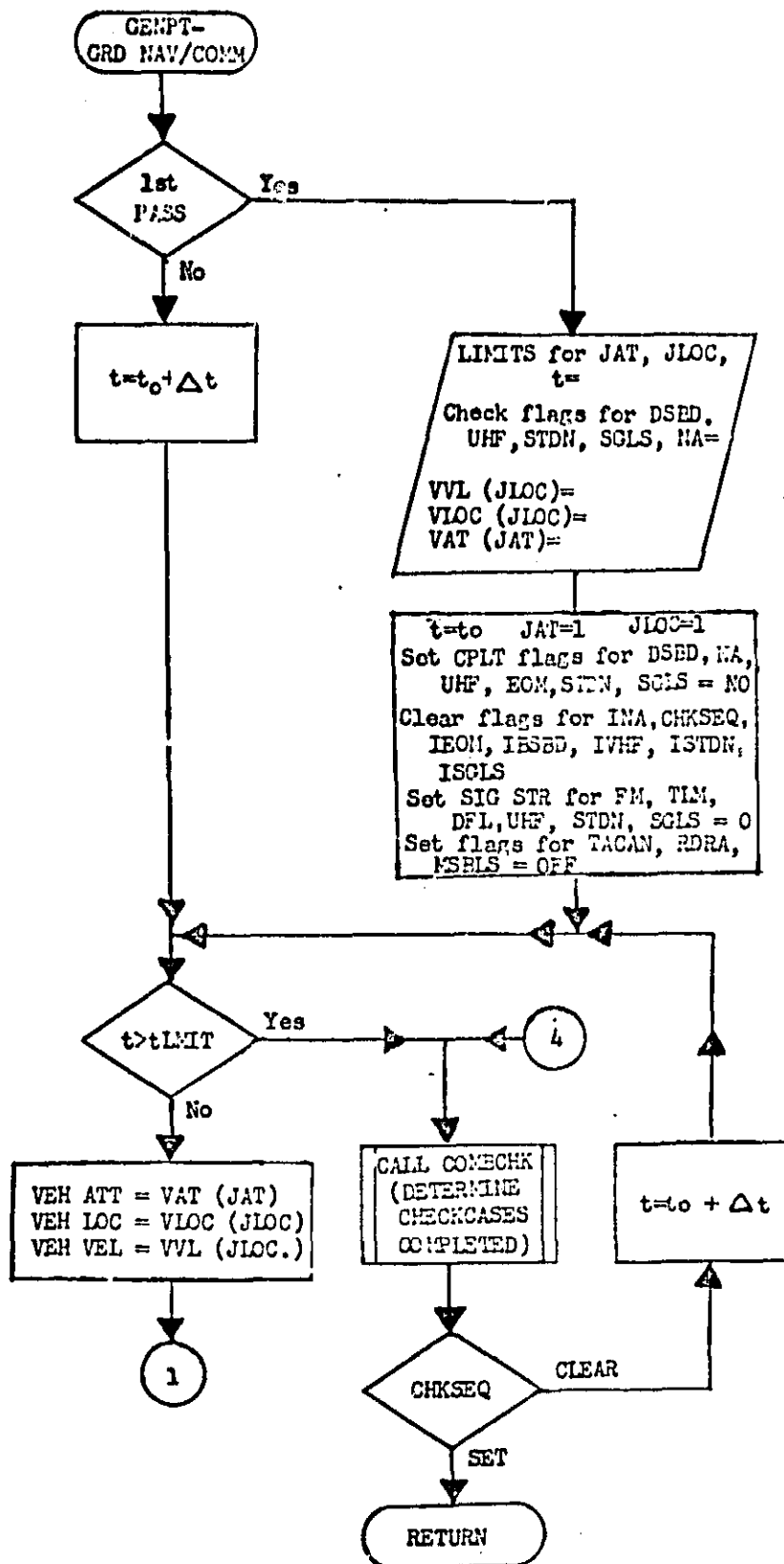


FIGURE 2-6. GENPT - GRD NAV/COMM FLOW CHART

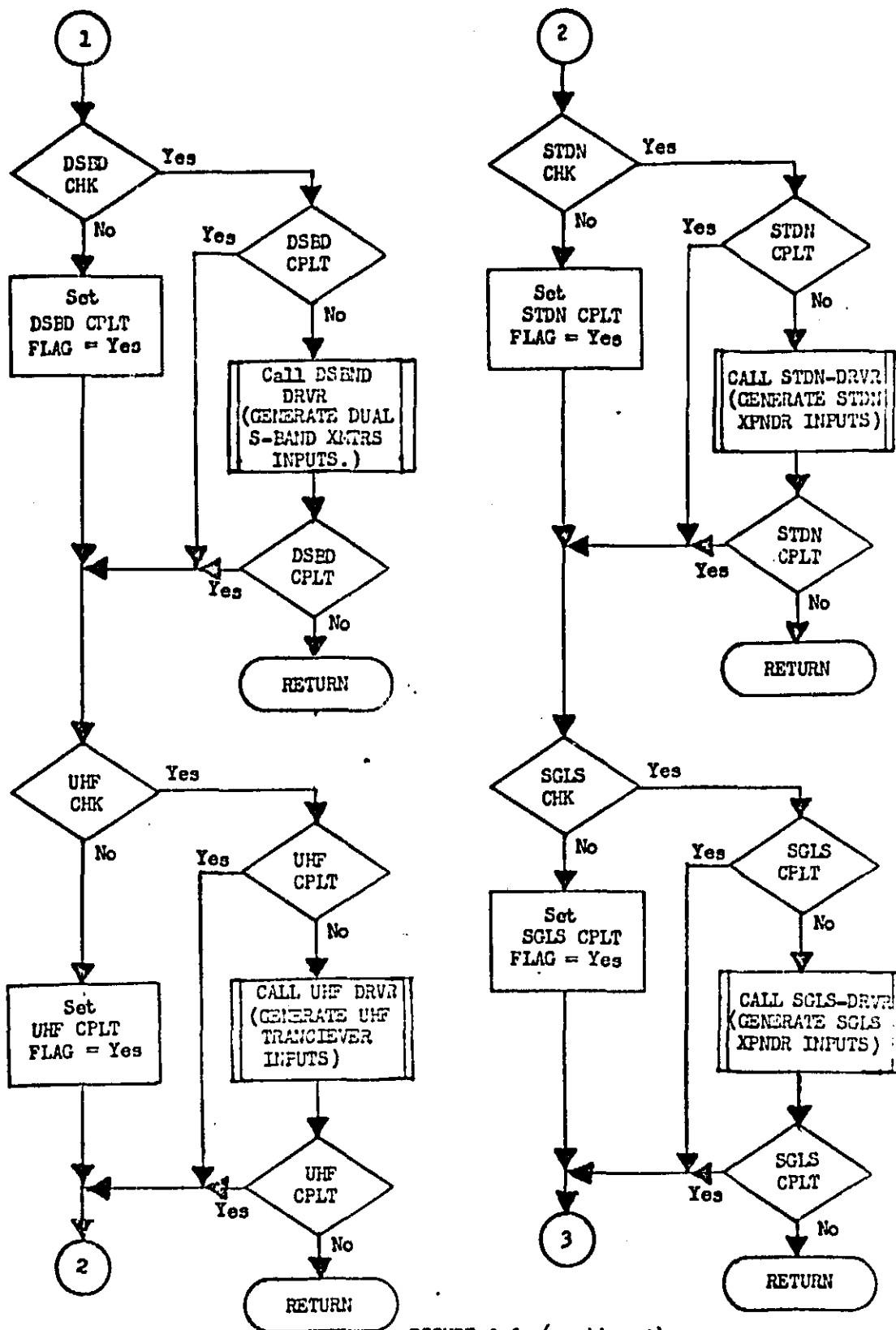


FIGURE 2-6. (continued)

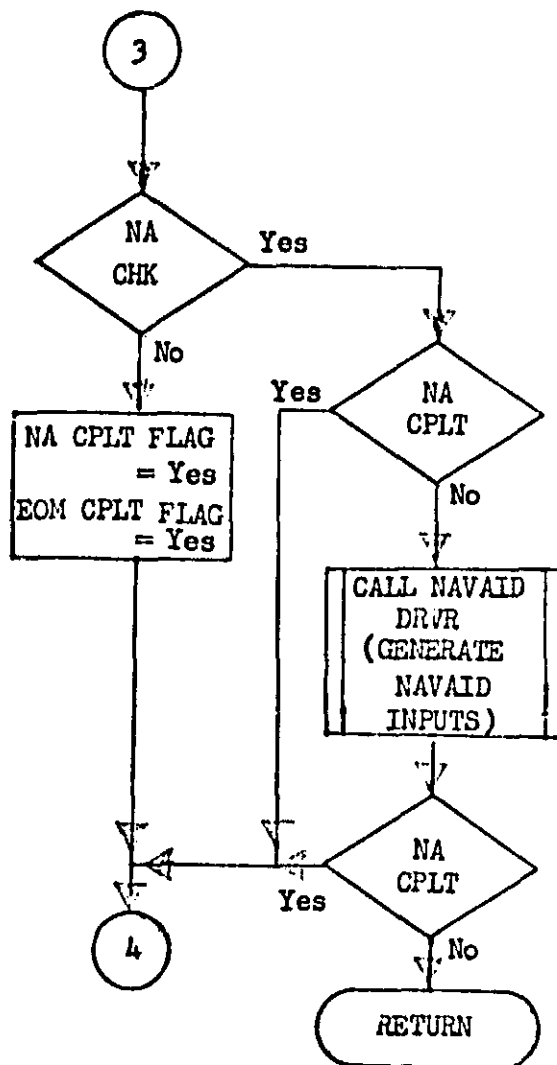


FIGURE 2-5 . (complete).

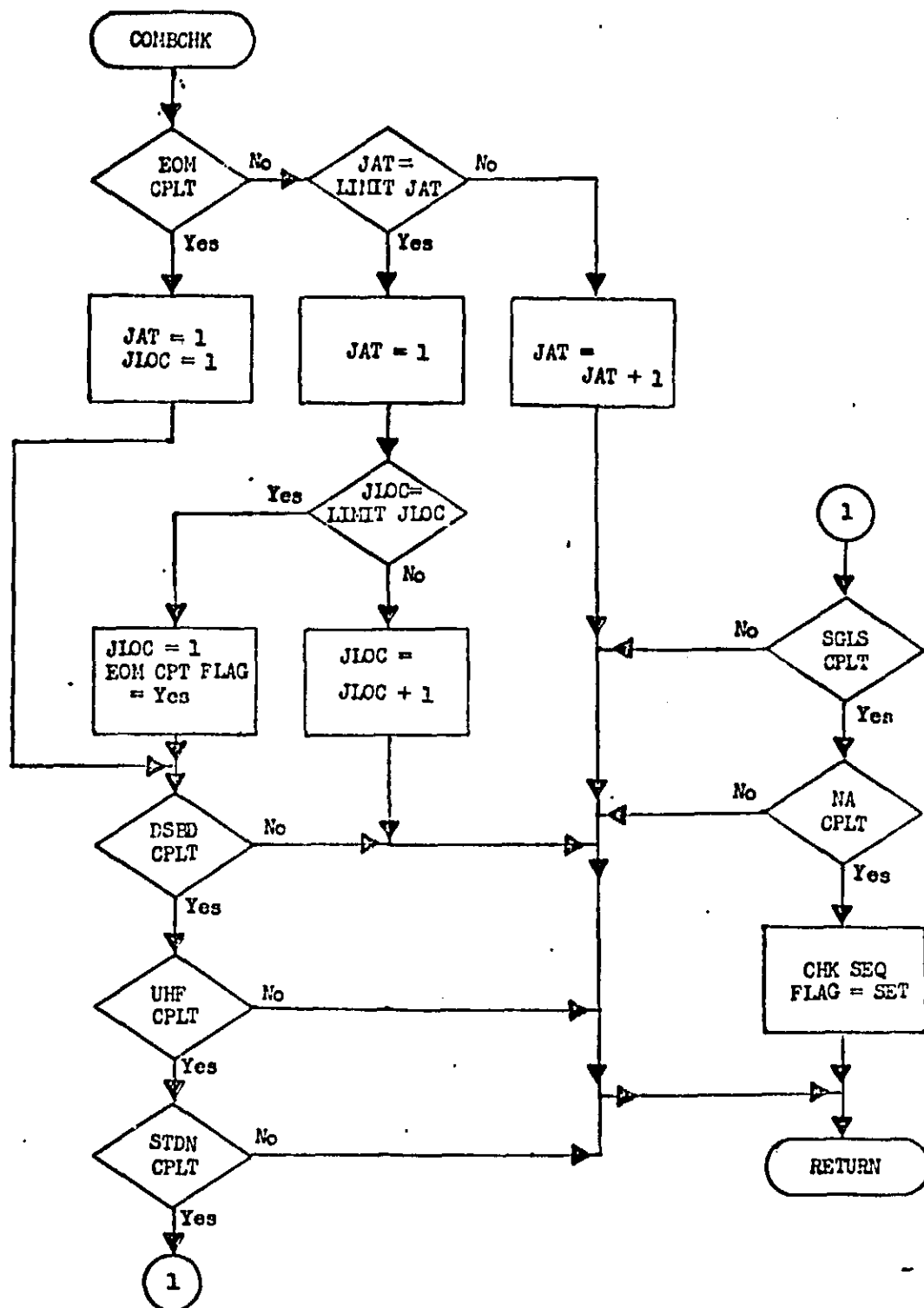


FIGURE 2-7. COMBINATIONS COMPLETE CHECK (COMBCHK) FLOW CHART.

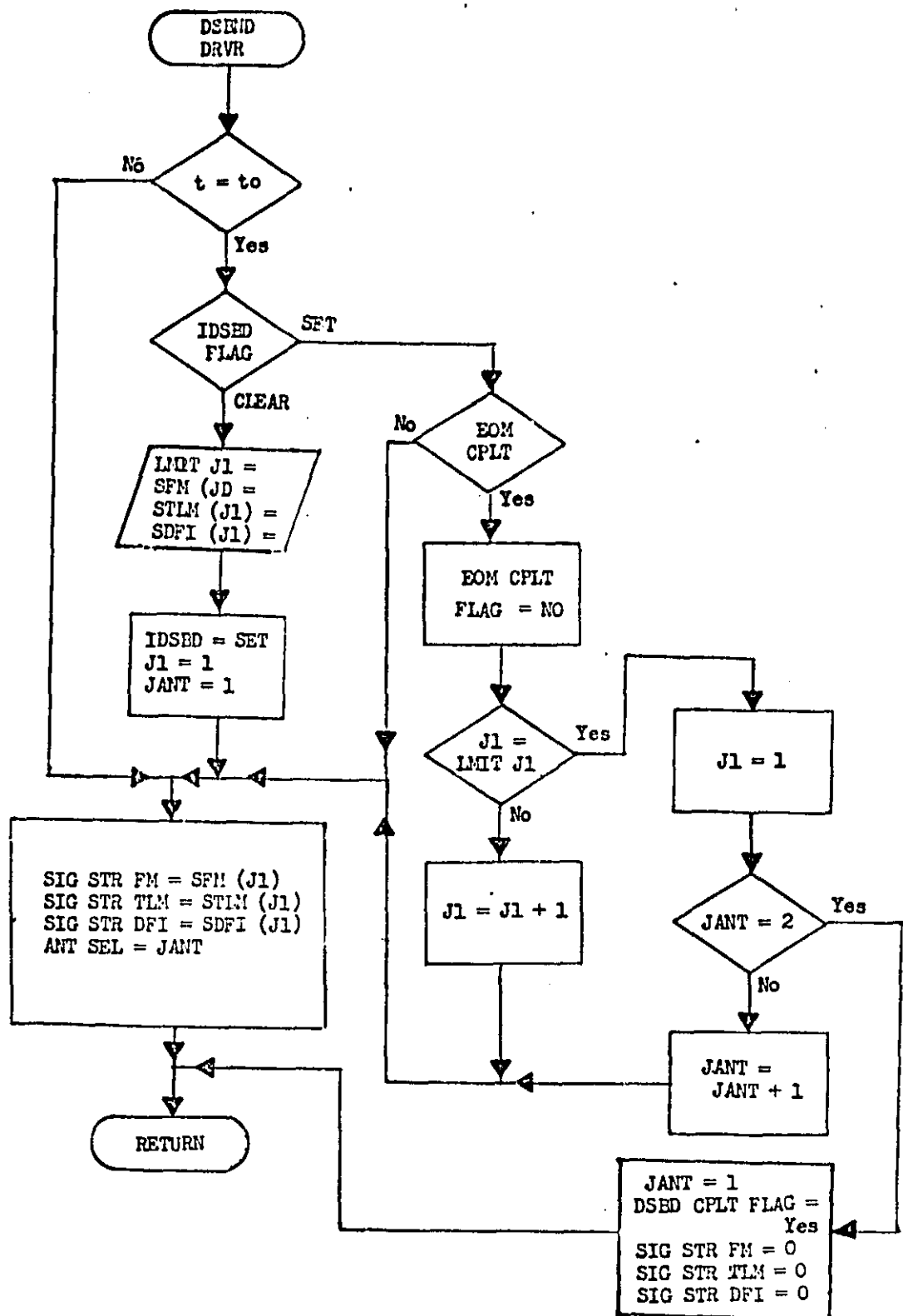


FIGURE 2-8 DUAL S-BAND DRIVER (DSBND DRV) FLOW CHART

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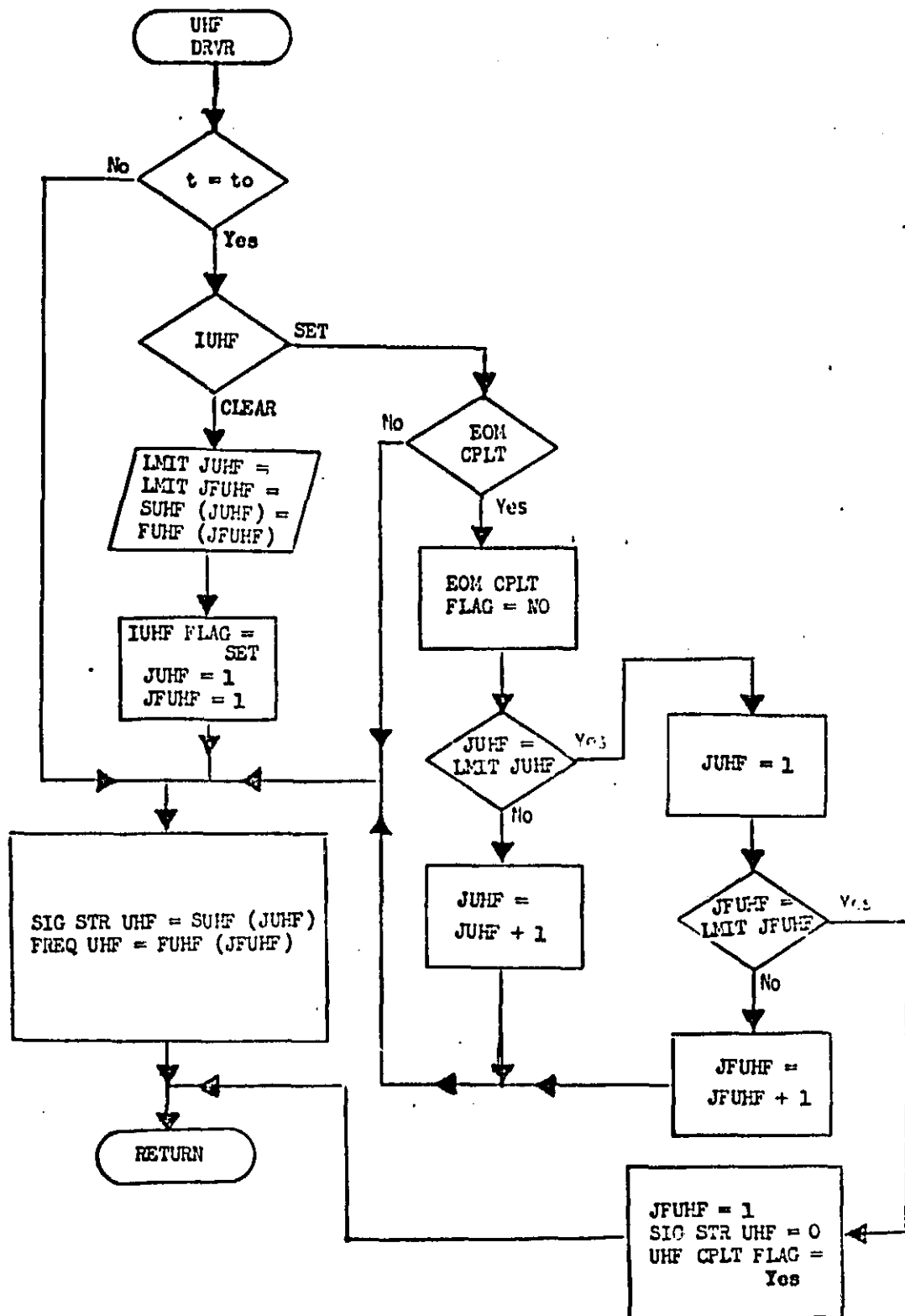


FIGURE 2-9. UHF TRANSCIVER DRIVER (UHF DRVR)
FLOW CHART.

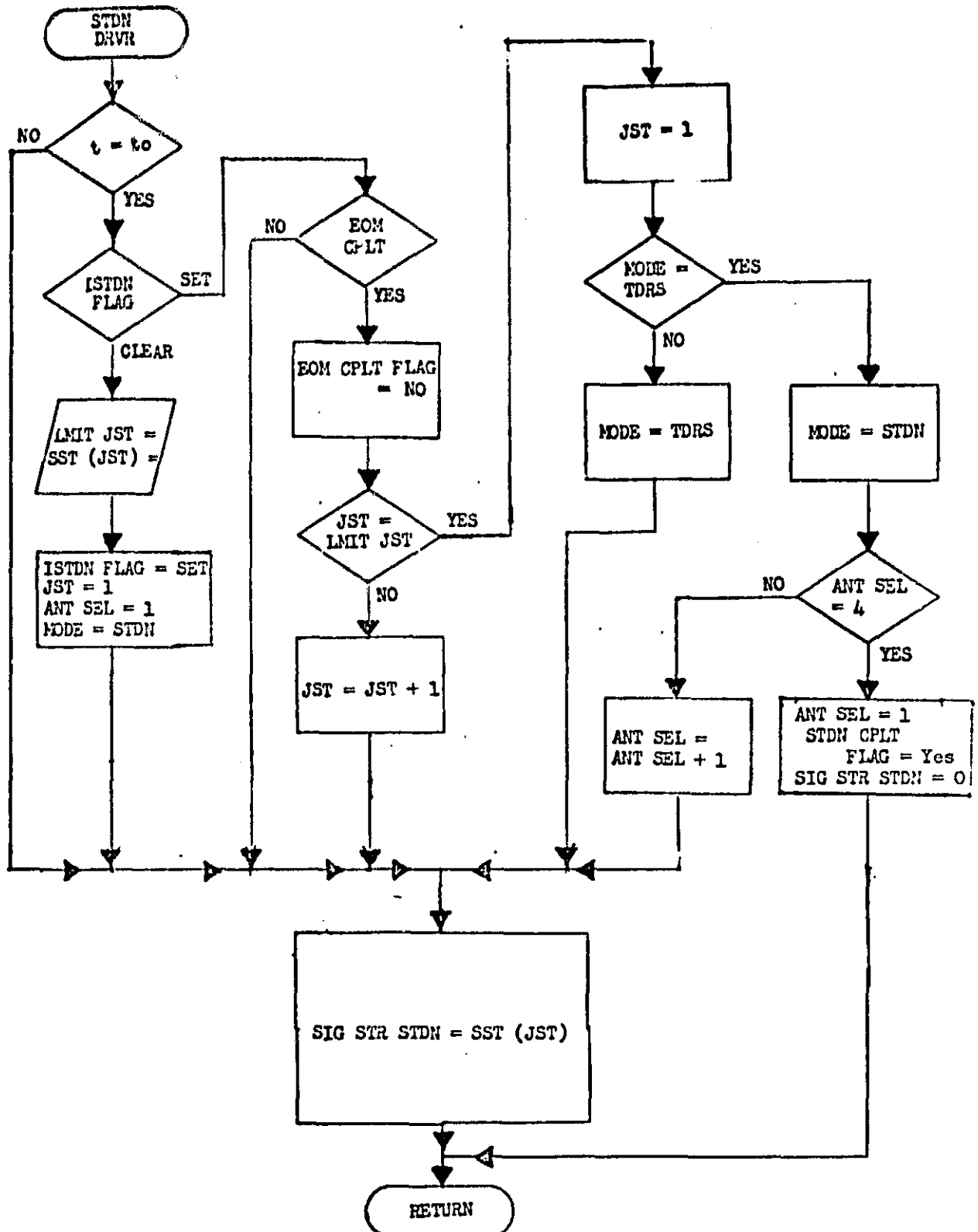


FIGURE 2-10. STDN/TDRS TRANSPONDER DRIVER (STDN DRV) FLOW CHART.

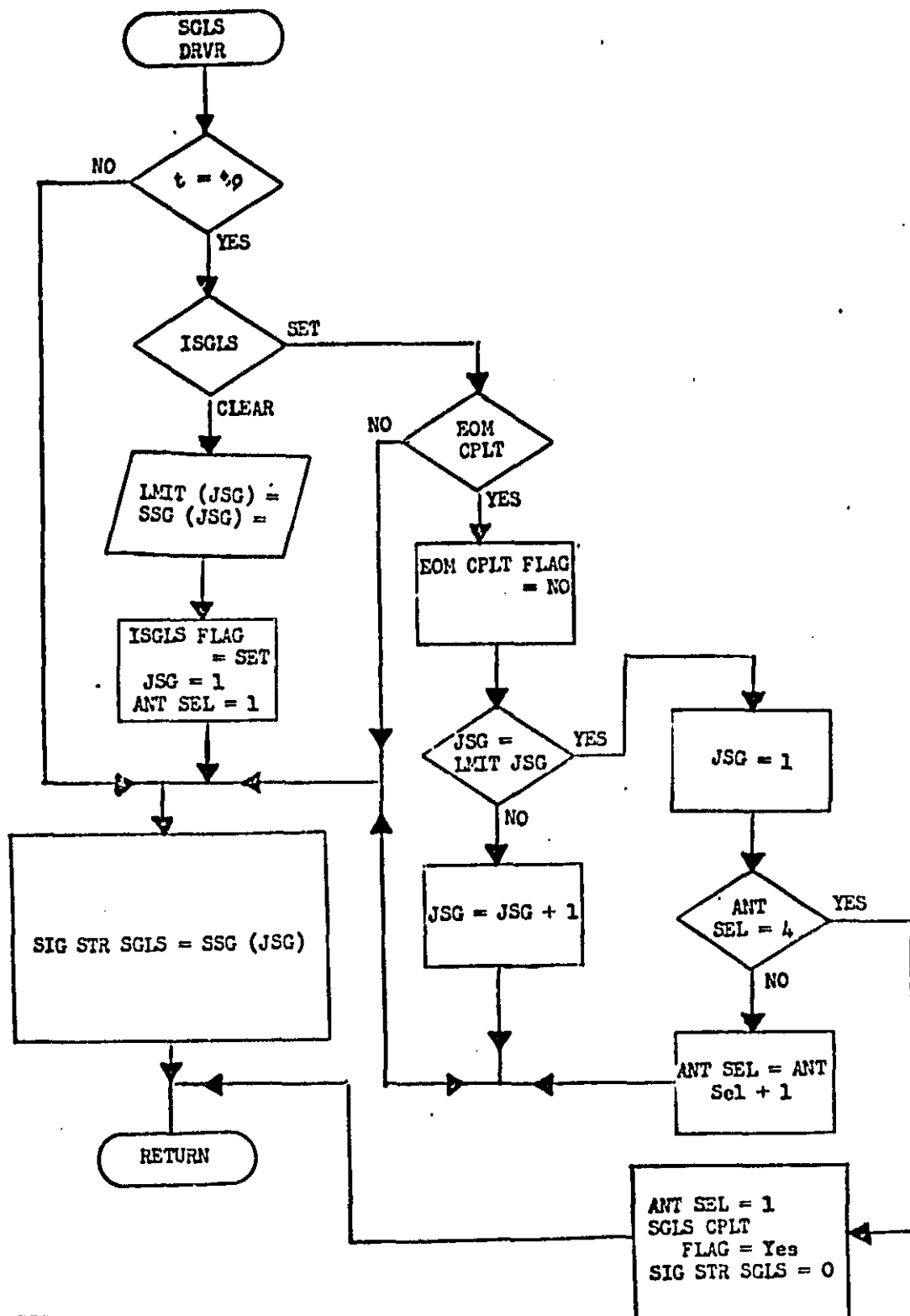


FIGURE 2-11. SGLS TRANSPONDER DRIVER (SGLS DRVR)
FLOW CHART.

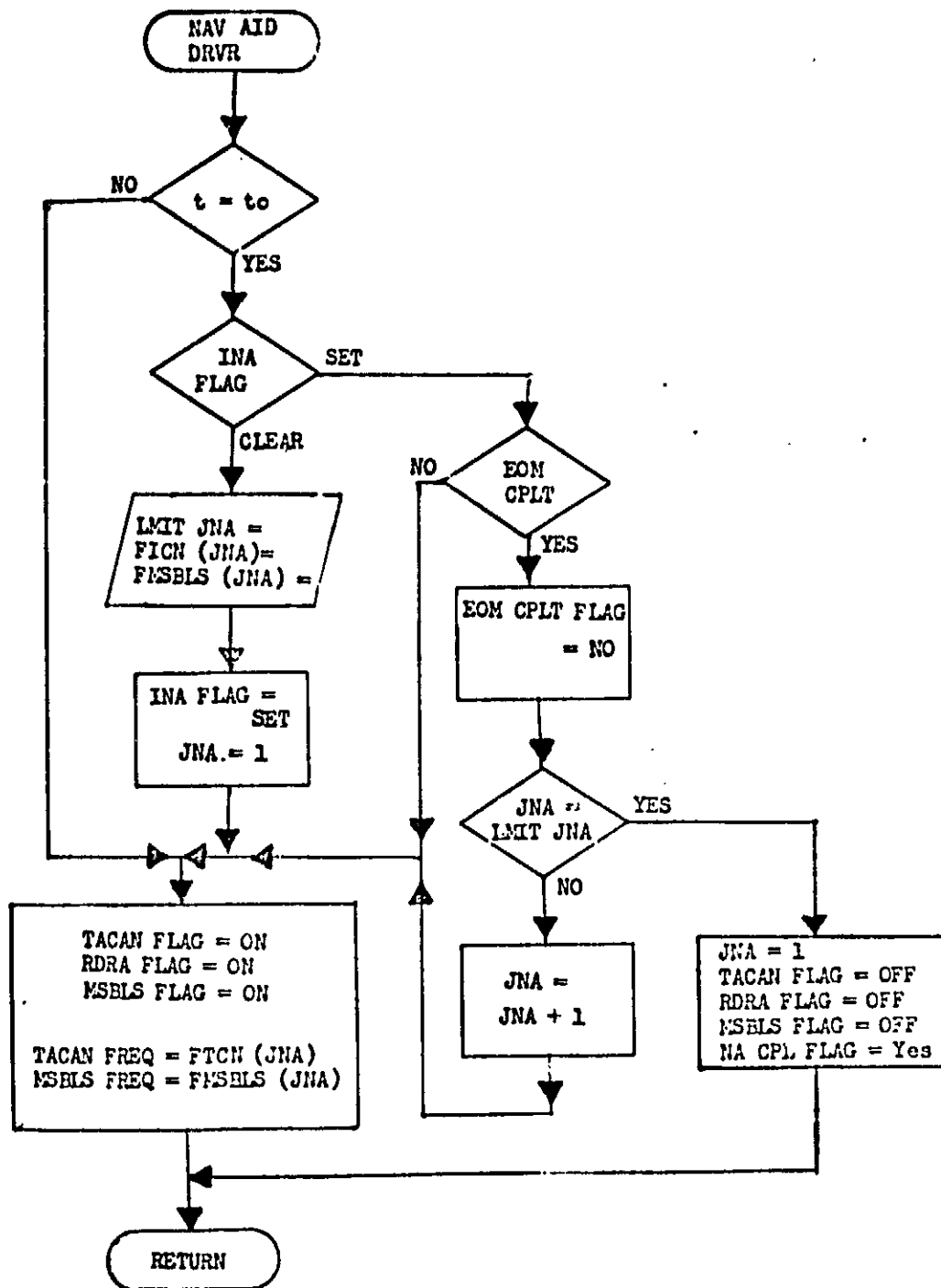


FIGURE 2-12. RADIO FREQUENCY NAVIGATION AIDS DRIVER (NAV AID DRVR)
FLOW CHART

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Provisions - This technique provides the following capabilities.

- Initialization of Parameters.
- Interfacing module drivers.
- Multiple evaluations during a single run.

At the start of each run, with the exception of the Equations of motion drivers, the interfacing module parameters are initialized to the "off" conditions. The parameters remain in "off" conditions until that portion of the module is selected for verification. When the portion has completed verification the parameters are again returned to the "off" condition.

Those input parameters normally provided by interfacing modules are provided by the module drivers. The values of the parameters are determined by the validator. Ground station locations, etc, data files will be accessed as required by the simulation module and therefore should not require a driver or any special verification. The following drivers were identified:

- Equations of Motion-provides shuttle vehicle location, attitude and velocity, etc.
- Dual S-Band Telemetry-provides antenna selection, and transmitted signal strengths.
- UHF -provides UHF frequency selected and transmitted UHF signal strength.
- STDN-provides mode selection (STDN or TDRS), antenna selection, and transmitted signal strength.
- SGLS-provides antenna selection and transmitted signal strength.
- NAV. AID-provide selected TACAN and/or MSBLS frequency, and TACAN, MSBLS, and Radar altimeter on/off selections.

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The Equation of Motion driver is active for each check case with a complete cycling of its conditions for exercise of each of the other driver (s) conditions. Each of the remaining drivers is cycled only once during each run with all other driver's conditions remaining constant. This allows the verification of any one or all portions of the module for a particular set of vehicle positions, altitudes, etc. This verification should thoroughly exercise the Ground station data files, locations, etc, in order to provide the correct answers.

2.2.2.2 Payloads and Rendezvous Targets

A variety of payloads and rendezvous targets will exist for possible use with the Shuttle Orbiter. This section provides a description of the Payload/Rendezvous Target Module. The description defines the Module functions, interfaces with other modules, associated parameters, and briefly discusses techniques for verification of the module performance.

System Description

A wide variety of possible rendezvous targets and payloads exist for the Shuttle missions. The variety of satellites, modules, upper stages, experiments, etc. include the following:

- Cryo tug
- Agena high energy payload
- Interim tug
- Large Space Telescope
- ESRO Space lab
- Earth observation satellite
- Shuttle Orbiters

A portion of the Orbiter payload may consist of Mission Extension Kits. These kits provide addition consumables such as fuel, oxygen, nitrogen, hydrogen, crew equipment, etc. necessary to allow additional stay in space. The functions provided by these kits are included in their support module and are not included in this section.

There are basically three modes of Payload Operation. These modes are stowed (retained), on-manipulator arms, and released modes. The released mode and Rendezvous Target operation are very similiar and will be combined for this discussion. The interfaces between the payload vehicle and the Orbiter for each of these modes are defined next.

Payload Stowed/Target Docked - The stowed/docked phase has the following interfaces with the Shuttle Orbiter systems.

- (a) Dynamics: The payload/Target Mass is integral with the Orbiter mass properties. There is a constant relationship between payload and orbiter attitudes, state vector, body rates, etc.
- (b) Electrical Power: The payload may receive electrical power from the Orbiter during this phase.

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(c) Environmental Control: The ECS may have several interfaces: A thermal heat load from the payload is supplied to the Orbiter Active Thermal control system via the Payload heat exchanger. Gaseous O_2/N_2 may be provided to the ARPCS. The Payload/Target volume may require pressurization and pressure control by the Orbiter ARPCS.

(d) Communications/Instrumentation: The communication between the Orbiter and Payload is via the umbilical. Interfaces include hardline audio (voice), video (TV) from payload camera, commands to payload from the Orbiter Payload signal processor, and instrumentation data from the payload to the Orbiter FM transmitter.

Payload/Target On - Manipulator Arms - During this phase of operation umbilicals are disconnected and all communications must be via Radio Frequency link.

(a) Dynamics: The payload mass properties are coupled to the Orbiter mass properties via the manipulator arms. The payload attitudes, rates, state vector, etc. are related to the Orbiter parameters. The relative range and attitudes affect communication and visual views.

(b) Communications & Instrumentation: The voice communications and commands from the Orbiter are transmitted via the Payload Interrogator RF link. There are two interrogators with 40 channels each. Twenty of these channels provide Air Force payload telemetry and command transfer capability. The interrogator (Orbiter) transmits two watts via a S-Band antenna with a limited antenna gain pattern. Minimum range and maximum range modes of operation are available.

(c) Visual: Out-the-window views and TV cameras provide optical information, concerning the payload configuration, relative range, and relative attitudes.

Payload Detached/Rendezvous Target - All communications are via the RF links.

- (a) Dynamics: The Payload/Target mass properties, attitude, state vector, etc. are independent of the Orbiter. The relative attitude and range influence the communications and visual views.
- (b) Communications/Instrumentation: Communication is via the Payload Interrogator, or S-Band transponders. Payload Interrogator functions are the same as in the on - manipulator arms mode. The S-Band transponders provide communication between two Shuttle vehicles. Communication includes voice, commands, or telemetry data transmitted via SGLS transponder (Air Force) or STDN/TDRS transponder (NASA).
- (c) Rendezvous Radar: The radar provides range, range rate, angle, and angle rate information during rendezvous. The radar operates in two modes: passive target (include passive enhanced) and active enhanced cooperative targets. The passive mode receives a reflected signal from the target for operation. The active mode is dependent on the target receiving, shaping, and returning the radar signal.
- (d) Visual: Similar to the on-manipulator-arms mode, with less detail apparent at increasing distances.

Payload/Target On-Board Systems - Shuttle payloads may include a wide variety of onboard systems - electrical, hydraulic, avionic, etc. Some of these systems will affect the visual configuration, attitude, or range.

For example the attitude control system would null rates, maintain attitudes, etc. which would stabilize the Target during rendezvous or docking. These on-board systems would be similar to shuttle systems, to be described in later reports. The parameters, techniques, etc., covered in the context of Shuttle onboard systems should be adequate for use for the Payload/Target on-board systems. Therefore no further effort will be expended on those systems.

Module Functions and Parameters

The Payload/Target Module provides the following functions:

- Umbilical interface logic
- Payload Interrogator interface
- Rendezvous radar interface
- S-Band transponder interface
- Payload/Target on-board Systems

Figure 2-13 identifies the module functional elements and their interfaces with other modules. The visual display model inputs are shown for completeness. The parameters associated with the module are presented in table 2-5. It should be remembered that the "on-board systems" element parameters are not included in the table. The functions of each of the functional elements are discussed below.

Umbilical Interface Logic - This module provides the enabling logic for payload video, hardline payload commands, audio communication, and payload instrumentation via the Orbiter FM transmitter. The logic is a function of umbilical connection, payload logic (electrical power, switch positions, etc.)

Payload Interrogator Interface - This module provides suitable response for communications via the Orbiter payload interrogator:

- Determines adequate signal strength from Orbiter - A function of transmitted power, transmitted antenna gain pattern, receiving antenna gain pattern, range vehicle attitudes, receiver sensitivity, line-of-sight, enabling logic, etc:
- Transmit/Signal Strength Flag - Function of enabling logic for payload transmitter.
- Enables Interrogator Commands - Function of receiver sensitivity and received signal strength.
- Enables Audio reception (via interrogator) - Function of received signal strength and receiver sensitivity.

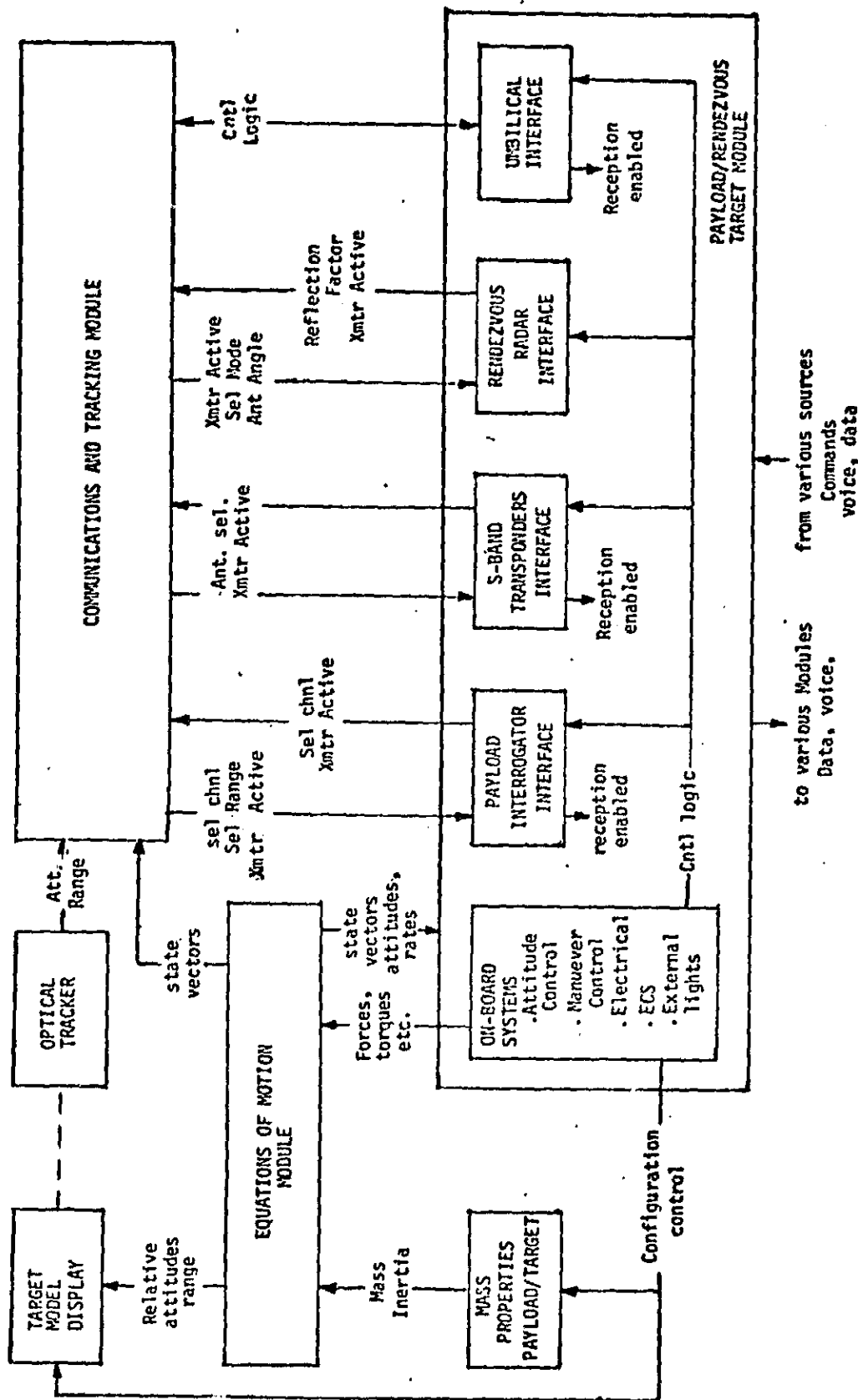


FIGURE 2-13. PAYLOAD/RENDEZVOUS TARGET MODULE, FUNCTIONAL ELEMENTS AND INTERFACES

TABLE 2-5. PAYLOAD/TARGET MODULE PARAMETERS

PARAMETER	TYPE ^a
Shuttle/Payload Umbilical connected/disconnected flag	I
Shuttle selected control logic Inputs	I
Vehicle positions, attitudes, velocities, rates (Shuttle, Payload/Target)	I
Shuttle Quad Antenna selection tags (S-Band)	I
Shuttle transmitter active flags (S-Band transponders, Radars, interrogators)	I
Shuttle selected STDN/TDRS transmission mode	I
Shuttle selected interrogator channel tag	I
Shuttle selected interrogator range max/min tag	I
Shuttle Radar antenna gimbal angles	I
Payload/target on-board systems input parameters	I
Shuttle Radar mode (transponder/reflection) tag	I
Payload/Target Received signal Strength (S-Band transponders, Radar, Interrogator)	CP
Payload/Target Reception enabled flags (S-Band Transponders, Interrogator, Umbilical)	CP
Target Radar signal reflection factor	P
Payload/Target S-Band transponders Doppler	CP
Payload/Target transmitter active flags (S-Band Transponders, Radar, interrogator)	P
Payload/Target On-Board Systems parameters (Instrumentation, Thrusters, Self-test, etc)	P
Payload/Target Mass properties parameters	P

^a Legend: I = Input
 P = Performance Parameter
 CP = Critical Performance Parameter

Rendezvous Radar Interface - The Rendezvous radar interface provides the following functions:

- Determines Radar signal Reflection factor - A function of vehicle attitude, incident angle.
- Determine adequate Received Signal Strength - A function of transmitted powers, vehicle attitudes, antenna gain patterns, range, line-of-sight, receiver sensitivity.
- Determine transmitted signal flag - A function of received signal strength, control logic.

S-Band Transponders Interface - There are two transponders: STDN/TDRS (NASA) and SGLS (Air Force) which provide the following functions.

- Determine adequate received Signal Strength - A function of transmitted signal strength, antennas selected, gain patterns of antennas, range, line-of-sight angles, receiver sensitivity.
- Enable/Disable command, voice, or instrumentation reception.
- Determine and output transmitted signal Strength flag - Function of on-board control logic.
- Determine Doppler - Function of received signal strength, ranges, range rate.

Module Verification

The verification of the Payload/Rendezvous Module can be accomplished using the basic technique developed for other systems module. Figure 2-1 provides a flowchart for this basic technique. The technique involves the generation of module input and initialization data via drivers (program GENPT) for each checkcase or condition for which a reference exists. The reference (program CHKMOD) may be specific test results, analysis results, independent simulation results, etc. The reference data and the simulation results for each checkcase are compared (program DSPLAY), and output for evaluations of accuracy and future reference. By proper design of the input drivers and checkcase conditions a thorough evaluation can be made.

From Figure 2-13 drivers for the following functions (interfaces) will be required:

- Equations of Motion
- Payload/Target mass properties
- Payload/Target on-board systems conditions
- Command Generator
- Payload interrogator
- Rendezvous Radar
- S-Band transponders (SGLS and STDN/TDRS)
- Umbilical Control logic

The following types of data will be required to develop reference checkcases or direct use as a reference.

- Antenna gain and patterns - This data should be available from analysis and scale model tests, and should eventually appear in reference 8. The other results would be included in the specific test report or analysis report.
- Transmitter output power - The actual output radio frequency power would be available from design analysis and acceptance testing of the transmitters, and should eventually appear in reference 8. The test reports and analysis results would normally be available from equipment or vehicle contractor.

- Receiver sensitivity - This data should be available from design analysis, and acceptance testing of units, and should eventually appear in Reference 8. The equipment manufacture or vehicle contract should supply the test reports etc.
- Control logic - Would normally be available from system schematics, wiring diagrams, analysis, and systems check-out or integrated testing.
- Radar signal reflections factors (coefficients) - data for various incident angles, directions for the various rendezvous targets. This data could be available from analysis or possibly model testing or other simulations.
- Radio frequency cabling and switch losses - The power loss within the vehicles due to the cable lengths, etc. This type data should be available from analysis of cable types, lengths, or from systems tests. This data would normally be available from vehicle contractor system designers and manufacturing personnel.

2.2.2.3 prelaunch/Launch Interface

Several interfaces exist between the ground (launchpad) and the "stacked" Orbiter, External Tank, and Solid Rocket boosters during the final phase of the launch countdown. This section provides a description of the functions for possible simulation.

This section also defines the module functions, associated parameters, and interfaces with other modules, and discusses briefly a technique for verification of the module performance.

System Description

The Prelaunch/Launch Interface provides the ground controls interface available via the two launch umbilicals (see reference 10), radio frequency interface, and the mechanical "inhibits" (such as vehicle strap downs) to the Orbiter/External Tank/Solid Rockets configuration. These interfaces are those available to the configuration during the period T-2 hours to launch phase of the countdown. The system interfaces are as follows:

- Communication and Instrumentation
- Electrical Power
- Environmental Control
- Hydraulics
- Propulsion
- Mechanical

These functions are considered for simulation in the Prelaunch/Launch interface module.

Communications and Instrumentation - Those interfaces available are the hardline commands, hardline telemetry, radio frequency commands, radio frequency telemetry, and radio frequency voice.

Electrical Power - Electrical DC bus power to the Orbiter's three buses is available via the launch umbilical. Ground support equipment also provides GH_2 and GO_2 to the Power Reactants distribution system to supply fuel cell and environmental gas during the prelaunch phase (Reference 7).

Environmental Control - Purge lines (see Reference 9) are provided for GN_2 structural and bay area purges, External Tank cryogenic disconnects GH_2 purge, and entry GHe purge (windshield, front wheel well.) The umbilical also provides lines for circulation of coolant fluid to the GSE heat exchanges (see Reference 11) interfacing with the Active Thermal Control Freon subsystem (Primary and Secondary).

Hydraulics - The launch umbilical provides lines for auxiliary power unit helium fill. It also provides hydraulic fluid lines for the circulation of hydraulic fluid by a GSE pump, (See References 12 and 13).

Propulsion-Lines are available to provide External Tank LH_2 and LO_2 fill/drain/dump, and prepressurization functions; GN_2 MPS purge; and MPS helium supply.

Mechanical - The mechanical release of the launch umbilicals, launch umbilical doors, and vehicle strapdowns occur at approximately $T=0$.

Prelaunch/Launch Interface Module Functions and Parameters

Figure 2-14 provides an overview of the Prelaunch/Launch module functional elements and interfaces with other modules. The module performs functions associated with the following activities:

- (a) Communications and Instrumentation
- (b) GSE Electrical Power
- (c) Environmental Control
- (d) Hydraulics
- (e) Propulsion
- (f) Control logic

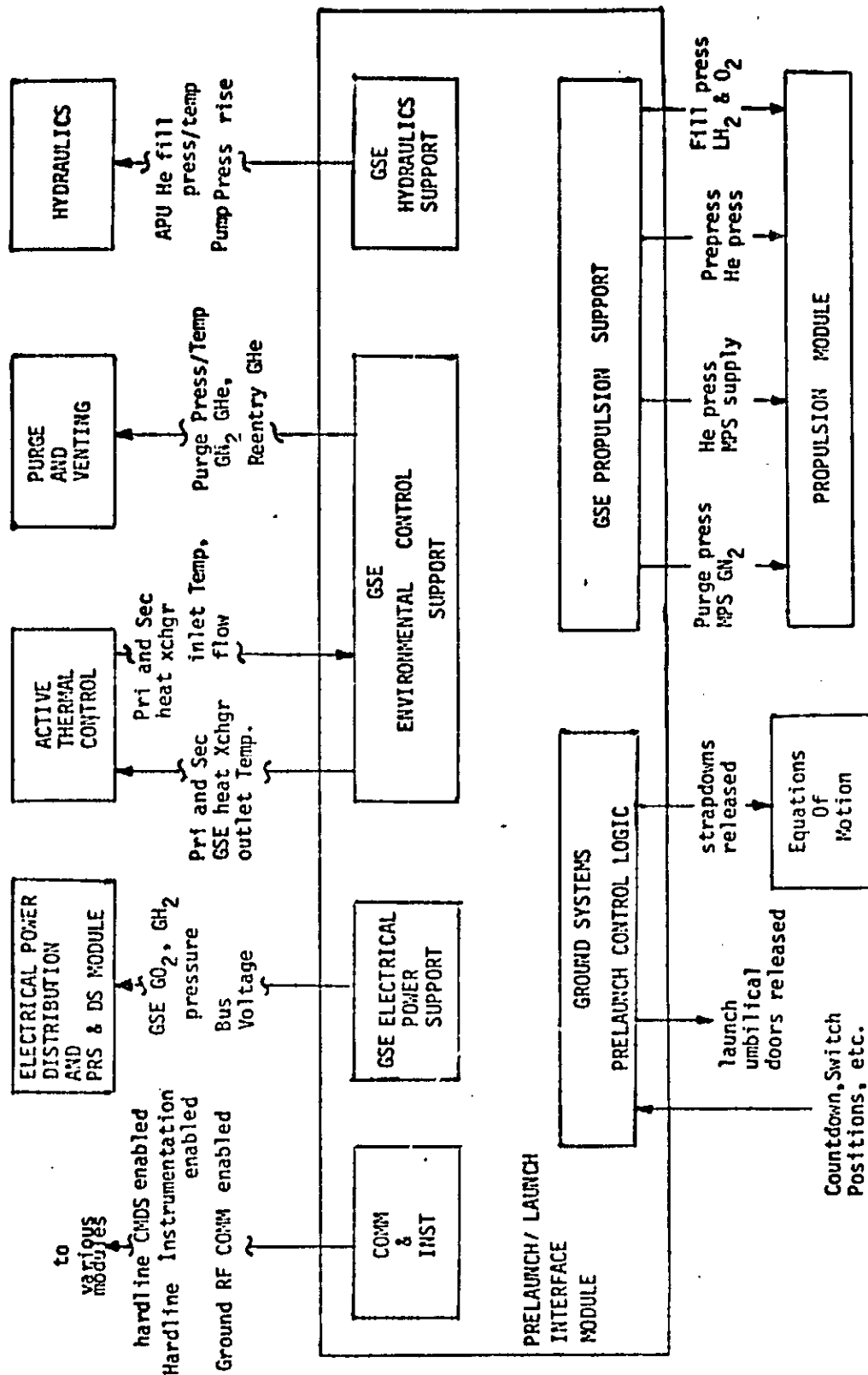


FIGURE 2-14. PRELAUNCH/LAUNCH INTERFACE MODULE, FUNCTIONAL ELEMENTS AND INTERFACES.

Table 2-6 provides a listing of the parameters associated with the module and a designation of parameter type. The functions performed by each element and the factors involved in calculations are as follows:

Communications and Instrumentation - This element provides the logic for launch/prelaunch enabling of Launch Umbilical Commands, instrumentation and ground functions involved in the radio frequency communications (voice, telemetry, commands). These functions are dependent on the ground facilities configuration, switch selections, etc.

GSE Electrical Power - This element defines the value of the GSE-supplied bus voltages and Power Reactants Storage and Distribution GSE supplied pressure for GO_2 and GH_2 . These outputs are functions of the ground equipment control logic, countdown timeline, etc.

Environmental Control Support - The ECS support outputs the GSE supplied pressures and temperatures are functions of the ground control logic, etc. In addition it also provides the GSE heat exchange fluid outlet temperatures to the Active Thermal Control Subsystem (Primary and Secondary loops). The temperature is dependent on the Orbiter loops fluid flow rate and GSE heat exchanger inlet temperature, GSE control logic, and heat exchanger heat transfer properties.

GSE Hydraulic Support - This element provides the GSE fill pressure and temperature for the Auxiliary Power Unit He fill. This pressure and temperature are determined from the GSE control logic. The element also provides the GSE hydraulic pump pressure rise for driving the Orbiter hydraulic systems during prelaunch. This pump pressure is related to the GSE control logic.

GSE Propulsion Support - The element determines the GSE supplied pressures and temperature for the following activities:

- MPS GN_2 Purge
- MPS He supply
- He prepressurization

TABLE 2-6. PRELAUNCH/LAUNCH INTERFACE MODULE PARAMETERS.

PARAMETER	TYPE ^a
Ground launch control input logic (countdown, GSE Switches, etc.)	I
Active Thermal Control loops inlet temperatures and flow rates to GSE heat exchangers (Pri and Sec)	I
Active Thermal Control loops outlet temperatures from GSE heat exchanger (Pri and Sec.)	CP
GSE Supplied bus voltages (to Orbiter buses 1,2,3)	P
GSE Hydraulics pump(s) pressure rise	P
GSE Supply Pressures/Temperatures to PRS&C (GO ₂ and GH ₂)	P
GSE fill pressures/temperatures (LH ₂ , LO ₂ , APU GHe)	P
GSE MPS He supply pressure/temperature	P
GSE MPS Prepressurization pressure/temperature	P
GSE Purge Pressures/temperatures (GN ₂ , GHe MPS ² GN ₂ , Reentry GHe)	P
Vehicle strapdowns released	CP
Launch Umbilical Doors released	CP
Launch Umbilicals Instrumentation Reception enabled	P
Launch Umbilicals Commands enabled	P
Ground RF Communications enabled	P

^a Legend:

I = Input

P = Parameter

CP = Critical parameter

- GO_2 fill
- GH_2 fill

These pressures and temperatures are functions of the ground equipment capabilities and the GSE control logic.

GSE Prelaunch Control Logic - This element performs the logic functions required to control the various prelaunch activities. It generates the logic for enabling prelaunch communications, instrumentation, command transfers for strapdown releases, lift-off indication, engine start, etc. per the countdown sequence.

Prelaunch/Launch Interface Module Verification

The drivers required to provide the necessary inputs for verification are:

- GSE Control logic Inputs
- Active Thermal Control - GSE Heat exchanger inlet fluid temperature and flowrate.

These drivers are used to provide the inputs. The module outputs are compared to the expected prelaunch ground interface values.

The electrical power voltages and the purge, supply, and fill pressures and temperatures can be determined from the ground support equipment capabilities, and planned inputs. These can be determined from the checkout procedures, countdown procedures, and GSE equipment specifications (not identified at this time).

The prelaunch sequences, and countdown procedures, time-line, etc. should provide the necessary information to verify the Prelaunch Control logic. These documents are not currently available and have not been identified. The values of the gas pressures, temperatures, will most likely be static during the time frame for the simulation and approximating the systems maximum operating pressures.

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2.3 CREW STATION MODULES

Visual and motion simulation are of crucial importance in the crew's subjective perception of the fidelity of representation of the real world. However, objective validation of visual/motion driver modules is made difficult by the highly hardware-peculiar nature of these modules. This section briefly describes the subject modules and their interfaces with simulation hardware and software, and makes some suggestions for validation at the module level. Techniques for integrated validation of visual and motion systems will be discussed in a later report.

2.3.1 Visual Drives

2.3.1.1 Module functions and parameters

Figure 2-15 provides an overview of the interfaces between the various visual-drive submodules and the rest of the simulation. Selection logic for the various sources of visual-scene information -- earth globe, terrain model, CIG, etc. -- is based upon mission-phase and operational-mode discretelys, as well as the current state. Each visual-scene source has its own driver module, which may include coordinate transformation, scaling, compensation, and mechanical limit checks. The driver for the computer image generation (CIG) module, used for manipulator-arm visuals, will be somewhat simpler, since the CIG will do much of its own transformation and scaling, and does not require mechanical compensation or limit checks.

Table 2-7 provides a parameter list for the visual-drive modules.

2.3.1.2 Module Validation Exercises

In the absence of visual-system hardware, the following types of validation exercise can be performed on visual-drive modules:

- (a) Verify that the visual-system control module outputs the proper subsystem-level commands to the various submodules, for various combinations of state variables, mission-phase discretelys, and operational-mode discretelys.
- (b) For each submodule, graphically verify the correctness of transformation, scaling and travel limit checks over the range of parameters for which that submodule is to be employed. A three-dimensional plotting capability will probably be the most convenient way to handle these submodule outputs. Reference 31 describes an existing JSC

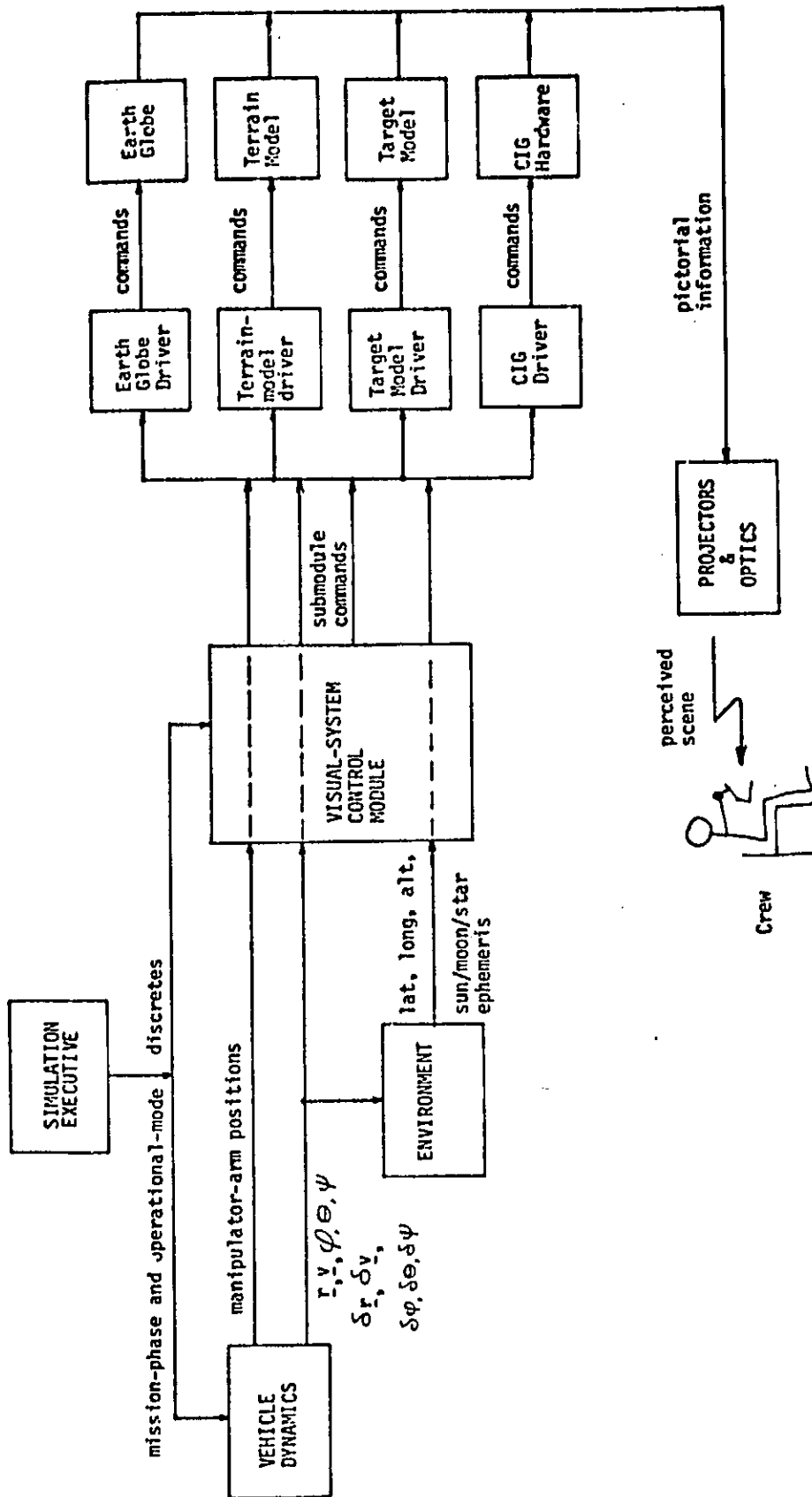


FIGURE 2-15. VISUAL-SYSTEM SOFTWARE INTERFACES

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TABLE 2-7. VISUAL-DRIVE MODULE PARAMETERS

SYMBOL	DESCRIPTION	TYPE ^a
r, v	Vehicle position & velocity vectors	I
φ, θ, ψ	Vehicle Euler angles	I
$\delta r, \delta v$	Multiple-body relative position & velocity vectors	I
$\delta \varphi, \delta \theta, \delta \psi$	Multiple-body relative Euler angles	I
-	Vehicle latitude, longitude, altitude	I
-	sun/moon/star ephemerides	I
-	Mission-phase and operational-mode discretes	I
-	Submodule activation commands	P
-	Visual hardware scaling, lags, limits, etc.	I
-	CIG imagery data base	I
-	earth globe position commands	CP
-	terrain model carriage & optical probe commands	CP
-	target model & camera track and gimbal commands	CP
-	CIG driver commands	CP

^aLegend: I = input
P = performance parameter
CP= critical performance parameter

software package which should provide adequate capability for this exercise.

2.3.2 Motion-Base Drives

2.3.2.1 Module functions and parameters

Motion-base drive software is even more hardware-dependent than visual drive software, for two basic reasons: First, the "synergistic" motion-base design recommended for Shuttle simulators (Fig. 2-16, from Ref. 24) does not allow any simple correspondence between vehicle degrees of freedom and actuator degrees of freedom. Motion in any individual vehicle degree of freedom -- roll, pitch, yaw, plunge, heave, or sway -- will require displacements of all actuators. Second, the limited actuator travel available prevents simulation of sustained accelerations. As shown in Fig. 2-17, the software must provide a look-ahead capability to gently "wash out" actuator commands without hitting displacement stops and causing an abrupt deceleration. Additional small-magnitude commands are used to "bleed back" the actuators to their null position, to provide travel freedom for the next large motion which may be required.

Table 2-8 provides a parameter list for the motion-base drive module.

2.3.2.2 Module Validation Exercises

It should be clear from the above description that objective validation of motion-base drive software is difficult or impossible, largely because the motion base does not provide an objective simulation of the real world. Rather, visual and motion (kinesthetic) sensations work together to provide a subjective simulation of the real world, as perceived by the crew. Visual/motion response should then be evaluated in terms of a "perceptual figure of merit" based upon such factors as their synchronization with each other, and correct initial response to the onset of an aircraft maneuver.

The bulk of this evaluation must of necessity be done in integrated operation. Initial validation and "tuning" of the software can be done using a simple linearized simulation of the motion-base hardware, comparative plots of vehicle and motion-base displacements, rates and accelerations, and automatic evaluation using a perceptual figure of merit.

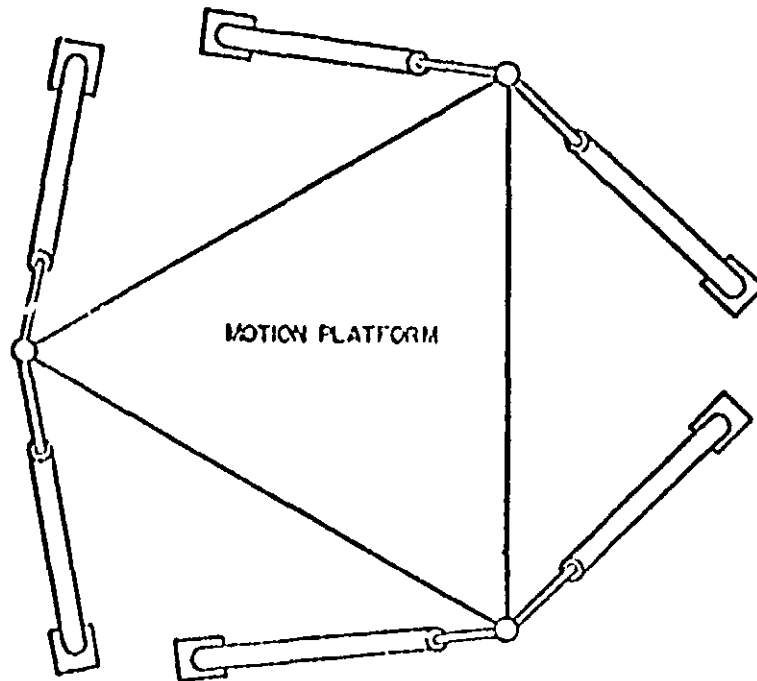


FIGURE 2-16. SYNERGISTIC MOTION-BASE CONFIGURATION

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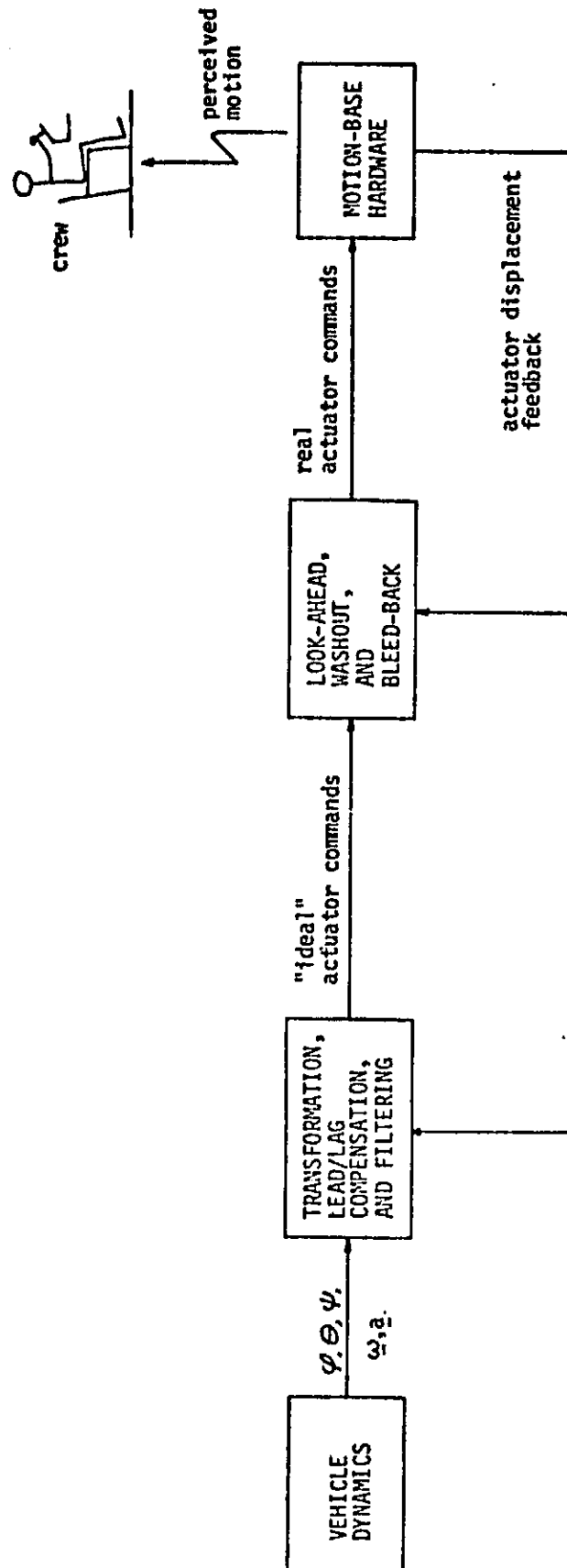


FIGURE 2-17. MOTION-BASE SOFTWARE INTERFACES

TABLE 2-8. MOTION-BASE DRIVE MODULE PARAMETERS

SYMBOL	DESCRIPTION	TYPE ^a
ϕ, θ, ψ	Vehicle Euler angles	I
ω	Vehicle angular-rate vector	I
\underline{a}	Vehicle acceleration vector	I
-	Hardware gains, lags, limits, etc.	I
-	"ideal" actuator commands	P
-	actuator-displacement feedback signals	I
-	real actuator commands	CP

^aLegend: I = input
 P = performance parameter
 CP= critical performance parameter

2.4 VEHICLE CONFIGURATION MODULES

The Shuttle vehicle undergoes discrete configuration changes compatible with each mission phase. Those simulation modules which are dynamically affected by configuration discretely are described in this section. These modules include Aerodynamics, Aerothermodynamics, and Mass Properties.

2.4.1 Aerodynamics

This section describes a reference module and an approach to be used in the verification of simulation aerodynamics modules. The technique presented provides verification of the aerodynamic force and moment calculations and the selection logic that defines the flight regime and vehicle configuration dependency. Verification of the simulation aerodynamics data base (i.e., the stored data tables) is out of scope of this study and the assumption is made that the tabular data has been previously verified.

Consideration is given only to the Shuttle vehicle aerodynamic forces and moments; however, the basic approach can be extended to include hinge moment calculations, the aerodynamic force and moment calculations for the separated solid rocket boosters and external tank, and to any other aerodynamic calculations.

2.4.1.1 Aerodynamics Reference Module Description

The reference module and the approach presented will provide data necessary for verification of simulation aerodynamics modules with respect to their calculation of the aerodynamic forces and moments that are sent to the equations of motion. The data provided consists of aerodynamic forces and moments for the full range of flight regime and vehicle configuration options. Modeling for the reference module is based on the Space Shuttle vehicle; however, module generalizations and the basic approach can be easily applied to other vehicles.

Aerodynamic modules can in general be broken into three major sections: 1) the logic and service routines necessary to retrieve the appropriate aerodynamic data from the tables, 2) the calculations necessary to compute the body axis forces and moments, and 3) the arrays containing the tabulated aerodynamic data. The verification techniques with the reference module presented apply only to the first two sections. It does not appear to be within the scope of this study to provide for the verification of stored data, and the assumption is made that all aerodynamic data tables have been previously verified. We anticipate that some project-level machinery will be employed for updating and validation of the "master" aerodynamic data file (i.e., the reference data tapes discussed in Reference 14). Also "customized" data files for individual simulators will probably be extracted from the master file by automated techniques; e.g., the use of program MOPAS (Matrix Oriented Production Assembly System). Differencing techniques could be utilized for the verification of tabular data, and would be directly applicable to data verification for the individual simulators. These techniques will be discussed in a future report.

The reference aerodynamic force and moment data is provided per indicated vehicle configuration and flight conditions. The major vehicle configuration change options are the three usual arrangements (1) Orbiter plus external tank (ET) plus solid rocket boosters (SRBs), (2) Orbiter plus ET, and (3) Orbiter alone.

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"Incremental effects" per indicated aero-surface positions, landing gear deployment, or drag chute deployment provide minor deviations in the vehicle configuration. Flight conditions include the relative wind conditions, the vehicle body rates, and the relative conditions between the vehicle and the ground/ET, or SRBs as appropriate to define ground/proximity aerodynamic effects during landing and separation respectively.

The online data arrays from which appropriate aerodynamic data is retrieved are initialized per the indicated vehicle configuration from a reference aerodynamic data file. In addition to these aerodynamic tables, data base requirements include the aerodynamic reference center-of-mass and the vehicle reference characteristics (mean aerodynamic chord (\bar{c}), lateral reference length (b), and the aerodynamic reference area (s)).

From an overview the reference module would replace the call to CHKMOD in the generalized verification executor, SOFCHK, presented in Figure 2-1 of this report. Check point data required to drive both the simulation module and the reference module would be provided by an appropriate checkpoint generation routine as is also indicated in Figure 2-1 of this report. The required check point data is discussed in section 2.4.1.3.

Table 2-9 presents the parameter list for the reference module and Figure 2-18 presents the corresponding math flow.

2.4.1.2 Aerodynamics Module Verification

The usual approach taken with respect to aerodynamic equation formulation is to model the "clean" vehicle with additive incremental effects due to deviations from the "clean" configuration (e.g., effects due to positioning of aero-surfaces, landing gear deployment, or drag chute deployment) or deviations from a free stream air flow (e.g., effects due to proximity of the SRBs, the ET, or the ground).

The need for modeling of individual effects and the related fidelity will in general vary from simulation to simulation. The respective verification task for each simulation dictates the use of a reference module of fidelity

TABLE 2-9. AERODYNAMICS REFERENCE MODULE PARAMETER LIST

PARAMETER	DEFINITION	TYPE ^a
CONFIGURATION	VEHICLE CONFIGURATION IDENTIFIER (INDICATES ORBITER+ET+SRBs, ORBITER+ET, or ORBITER)	I
FLIGHT PARAMETERS (M, α , β , V_A , q)	M-MACH NUMBER, α -ANGLE-OF-ATTACK, β -SIDESLIP ANGLE, V_A -VEHICLE VELOCITY RELATIVE TO AIR MASS, q -DYNAMIC PRESSURE	I
BODY RATES (p, q, r)	VEHICLE ANGULAR RATES (p-ROLL, q-PITCH, r-YAW)	I
RELATIVE CONDITIONS (GROUND, PROXIMITY)	RELATIVE CONDITIONS BETWEEN VEHICLE AND GROUND NECESSARY TO MODEL GROUND EFFECTS, RELATIVE CONDITIONS BETWEEN VEHICLE AND SEPARATED SRBs OR ET NECESSARY TO MODEL PROXIMITY EFFECTS	I
AERO-SURFACE POSITIONS (δR , δSB , δA , δE , δBF)	δR -RUDDER POSITION, δSB -SPEED BRAKE (FLARED RUDDER) POSITION, δA -AILERON POSITION, δE -ELEVON POSITION, δBF -BODY FLAP POSITION	I
LANDING GEAR AND DRAG CHUTE INDICA- TORS (DLG, DCHUTE)	DLG-LANDING GEAR INDICATOR FOR DEPLOYED/RETRACTED STATUS DCHUTE-DRAG CHUTE INDICATOR FOR DEPLOYED/NOT DEPLOYED STATUS	I
CENTER-OF-MASS (X_{CG} , Y_{CG} , Z_{CG})	CENTER-OF-MASS LOCATION IN VEHICLE BODY COORDINATE	I
AERO TABLES	TABULAR AERODYNAMIC DATA STORED AS FUNCTION OF ONE TO SEVERAL VARIABLES (DIFFERENT FOR EACH OF THE VEHICLE CONFIGURATIONS)	I
REFERENCE CENTER-OF- MASS (X_{CG} , Y_{CG} , Z_{CG}) _{REF}	AERODYNAMIC REFERENCE CENTER-OF-MASS CORRESPONDING TO DATA IN THE AERO TABLES	I
VEHICLE CHARACTER- ISTICS (\bar{c} , b, s)	\bar{c} -MEAN AERODYNAMIC CHORD, b-LATERAL REFERENCE LENGTH, s-AERODYNAMIC REFERENCE AREA	I
FORCE COEFFICIENTS (C_X , C_Y , C_Z)	TOTAL AERODYNAMIC FORCE COEFFICIENTS REFERENCED TO THE BODY AXIS SYSTEM	P
MOMENT COEFFICIENTS ($C_{l_{AC}}$, $C_{m_{AC}}$, $C_{n_{AC}}$) ($C_{l_{TC}}$, $C_{m_{TC}}$, $C_{n_{TC}}$)	AC-TOTAL AERODYNAMIC MOMENT COEFFICIENTS ABOUT THE AERODYNAMIC CENTER-OF-MASS, TC-TOTAL AERODYNAMIC MOMENT COEFFICIENTS ABOUT THE TRUE CENTER-OF-MASS	P
FX POWER BASE	POWER-ON BASE AXIAL FORCE	P
FORCES (F_X , F_Y , F_Z) _{AERO}	AERODYNAMIC FORCE COMPONENTS IN THE BODY AXIS SYSTEM	CP
MOMENTS (M_X , M_Y , M_Z) _{AERO}	AERODYNAMIC MOMENTS ABOUT THE TRUE CENTER-OF-MASS	CP

- ^a P - PERFORMANCE PARAMETER
 CP - CRITICAL PERFORMANCE PARAMETER
 I - INPUT

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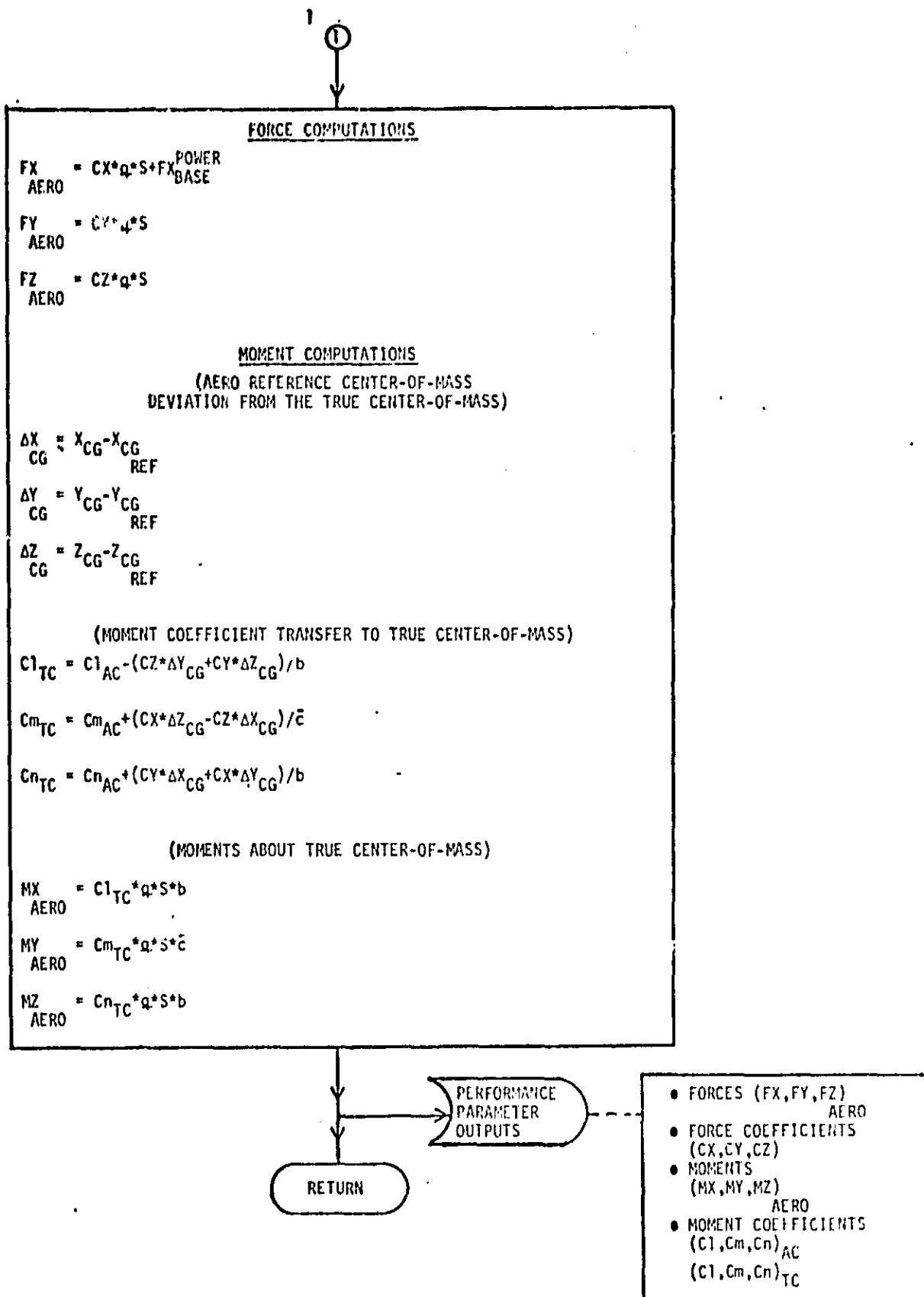


FIGURE 2-18 AERODYNAMIC REFERENCE MODULE (continued)

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greater than or equal to that proposed for the simulation module. (Simulation modules of less fidelity than the reference are not expected to match exactly, but verification can be accomplished through output data comparisons and engineering judgement.) Instead of attempting to identify the maximum simulation requirements and then developing a reference module of appropriate fidelity, the generalization is made to require that the reference module reflect the maximum fidelity available. Since the maximum fidelity for an aerodynamic model is determined by the availability of aerodynamic data, the approach presented is to utilize the reference aerodynamic data file as the data base and to use the aerodynamic equation formulations of the aerodynamic group (vehicle vendor or designated subcontractor) providing the data implemented on the reference file.

The math flow presented in Figure 2-18 indicates the simple structure suggested for the reference module. At the beginning of a check sequence the table arrays are initialized with the appropriate data per the indicated configuration; if any configuration changes are made in the course of a run, the reference module table arrays are re-initialized with the newly appropriate values. All force and moment calculations are the same for all combinations of configuration and flight regime. The equations represent the most general case with non-applicable effects zeroed either through aerodynamic data returned from table interpolations or through input variable specifications.

The generalized functions appearing in the math flow should be replaced with appropriate equations obtained from the vehicle aerodynamics reference source as previously discussed. The independent variables of the functions are indicative of the effects to be modeled. The addition or deletion of effects may be necessary or required per simulation requirements and consequently the reference module equation development should be coordinated with personnel defining simulation requirements and personnel performing aerodynamics studies.

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Implicit in the generalized functions shown for generation of the total coefficients is a series of table look-ups for retrieval of appropriate data. The table searches and interpolations will involve from one to three or even four variables. Service routines necessary to perform these functions are also a part of the reference aerodynamic module in the sense that they define a particular retrieval technique and thus an associated accuracy for returned data. An explicit verification for the counterpart table searches and interpolations of the simulation module is not provided. However, verification of the simulation service routines is provided indirectly through comparison of the output performance parameters.

The equations used to generate total body axis forces and moments from the previously computed coefficients assume a body axis system with "x" out the vehicle nose, "y" out the right wing, and "z" completing the right hand system. The vehicle body axis attitude rates and the aerodynamic moments have a positive sign convention consistent with a right hand system definition; sign conventions for control-surface deflections must be incorporated in the generalized functions.

Performance parameter data generated for comparison purposes consists of the body axis forces and moments and corresponding total force and moment aerodynamic coefficients; which are output to a data file for each check point. Post processing of the output data is discussed in the following subsection.

2.4.1.3 Verification Check Data

Check point input data for both the reference and the simulation modules should be generated and exist in storage for extraction by the check point generation routine. The complete sequence of check points should exercise all capabilities for each configuration and also exercise all possible transitions between configuration.

The suggested approach is to subdivide the check sequence into sub-sequences, each of which contains sequential check points over a "range of vehicle states" for a given flight regime. The individual "ranges of vehicle states" can then be chosen to exercise all vehicle configuration and flight regime combinations. The appropriate input parameter values for the check points can then be generated off-line by digital analysis programs and stored in arrays by subsequence to be retrieved as appropriate by the check point generation driver routine.

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The spacing of check points within an individual "range of vehicle states" and the spacing between the individual "ranges of vehicle states" is arbitrary and the only requirement is to include enough checkpoints per subsequence to provide a comparison plot for that particular subsequence.

In addition to the standard sequence of check points described above, the reference module can be easily driven by data generated in a previous simulation run. This provides a capability to verify the simulation aerodynamic performance in simulation situations suspected of possible inaccuracies.

The verification of the simulation aerodynamic performance can be handled the same as that for most other modules, namely by engineering judgement applied to comparison plots generated by post processing of output from the simulation and the reference modules.

2.4.1.4 Reference Module Requirements

The required data base items for the reference module include the tabular aerodynamic data and the corresponding reference characteristics of the vehicle. Reference aerodynamic data files (Reference 14) are available and can be used for the reference module aerodynamic table initializations. The corresponding vehicle reference characteristics are available from the aerodynamic data documentation used in development of the reference data files (e.g., the Aerodynamic Design Data Book as referred to in Reference 14).

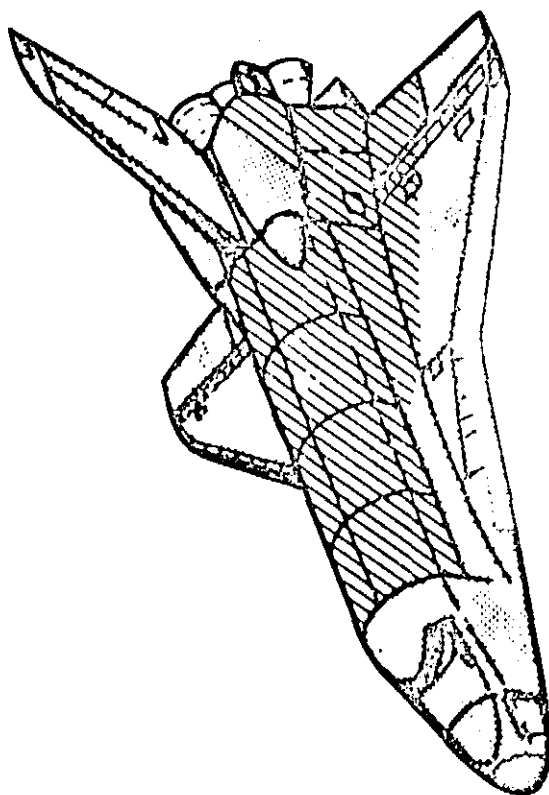
In addition, since equations for computing the total coefficients must be consistent with available data, the suggestion is to use equation formulations from the provider of the reference data available on the data tapes (i.e., the vehicle vendor). The vehicle vendor (or designated subcontractor) will have detailed aerodynamic models for use in design studies and the reference module model development can be reduced to a coordination effort by using these available vendor models.

2.4.2 Aerothermodynamics

This section discusses the functions and verification of the software module required to simulate the aerodynamic heating incurred by the Orbiter during entry and ascent. The Orbiter Thermal Protection System (TPS) is used to dissipate the heat flow due to aerodynamic heating. This prevents the primary aluminum structure from exceeding a temperature of 350°F (Reference 20). The baseline TPS consists of reusable surface insulation tiles bonded to the primary orbiter structure, as shown in Figure 2-19 (Reference 10).

The aerodynamic heating module will provide inputs to crew displays for the purpose of monitoring 14 critical bondline temperatures as shown in Figure 2-20 . The crew display method is via select CRT (Reference 22). Bondline temperatures will be computed by the aerothermodynamics simulation module and the results used for crew display, post-simulation analysis, and simulator module verification. The computed bondline temperatures will simulate readings taken by bondline thermocouples as depicted in Figure 2-21. The heat rate into selected orbiter compartments will also be computed as an input to the Active Thermal Control Subsystem (ATCS) module. Figure 2-22 shows the interaction between the aerothermodynamics module and other orbiter systems simulation software modules. Figures 2-23 and 2-24 describe the data flow through the aerothermodynamics module.

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LEGEND	
	LESS (ABOVE 2300°F)
	HRSI (BETWEEN 650 & 2300°F)
	LRSI (BELOW 650°F)
	LESS - INTERNAL INSULATION
	HRSI - FILLER BAR

FIGURE 2-19. ORBITER THERMAL PROTECTION SUBSYSTEM

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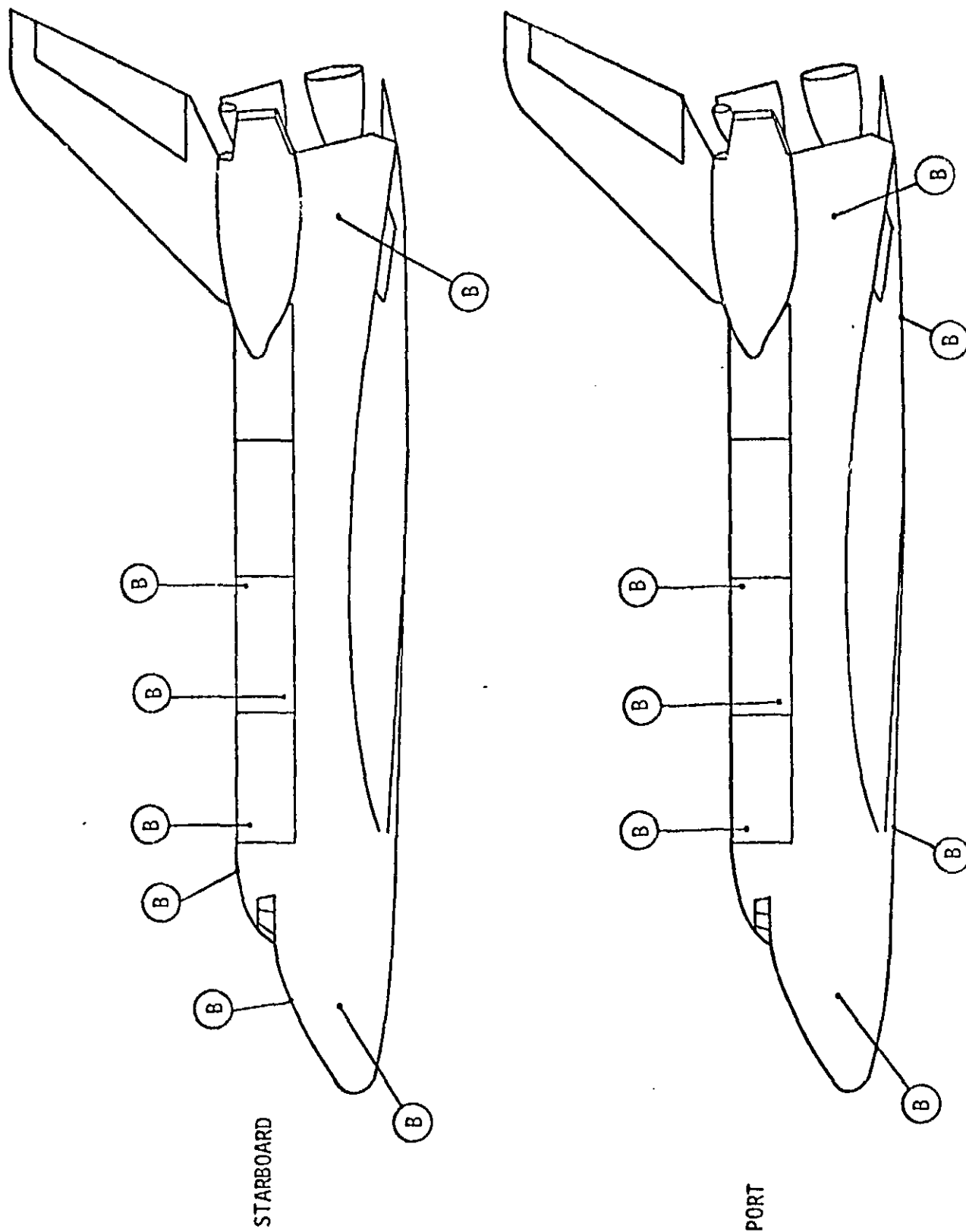


FIGURE 2-20. BONDLINE THERMOCOUPLE LOCATIONS

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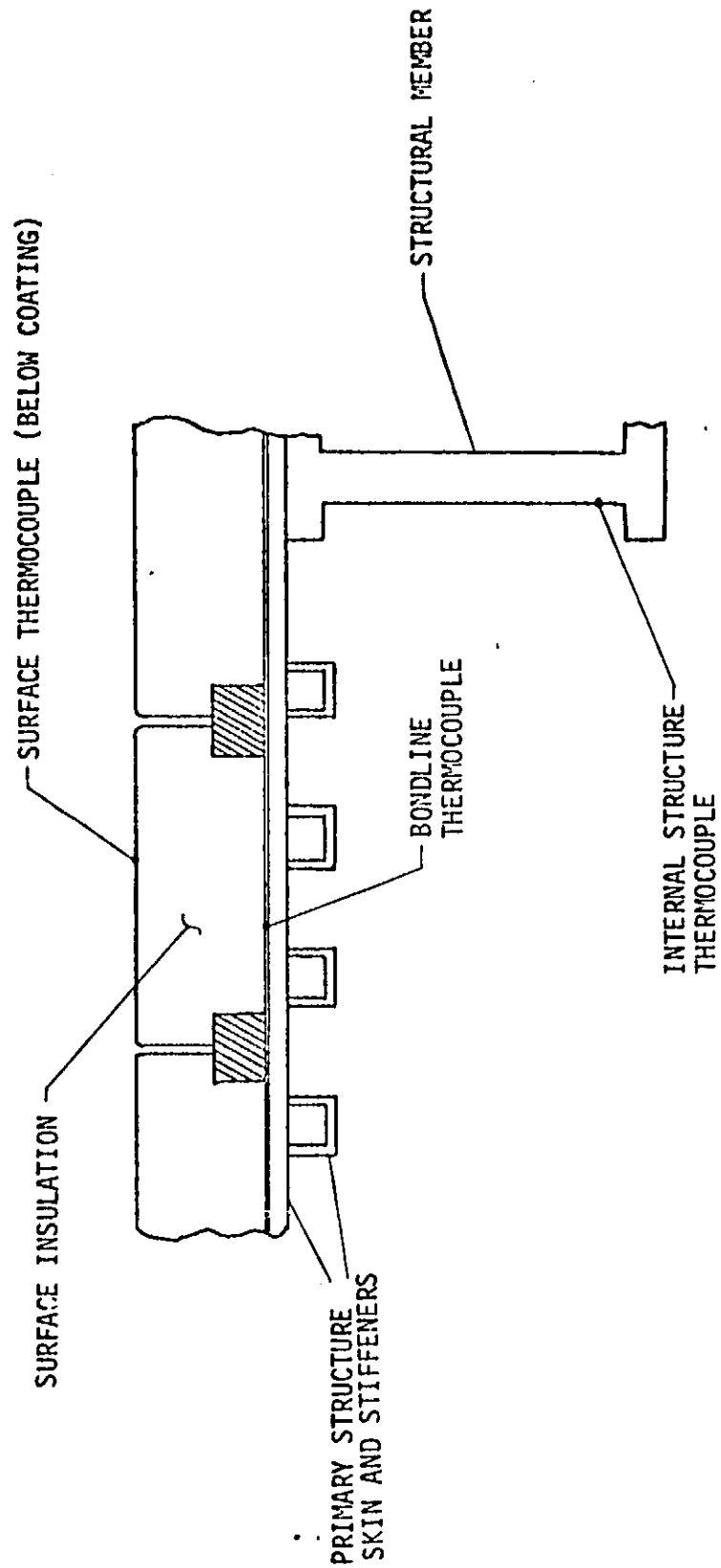


FIGURE 2-21. TYPICAL THERMOCOUPLE TYPE LOCATIONS

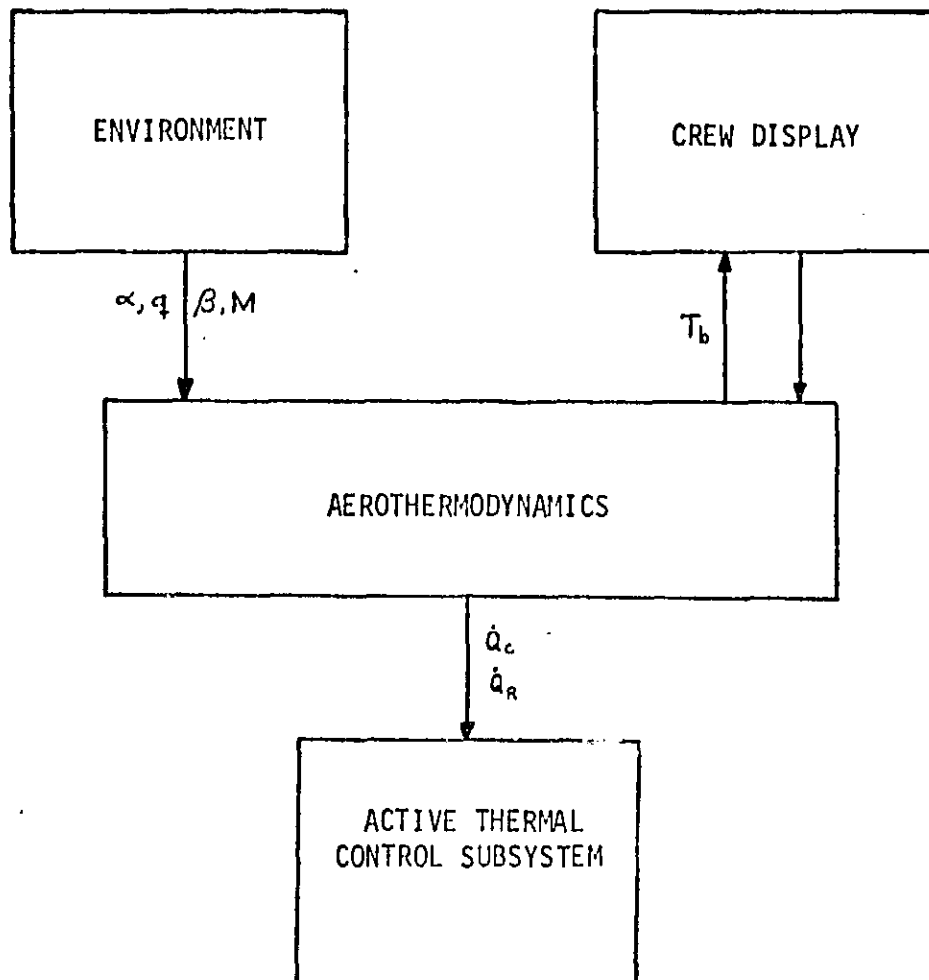


FIGURE 2-22. MODULE INTERFACES

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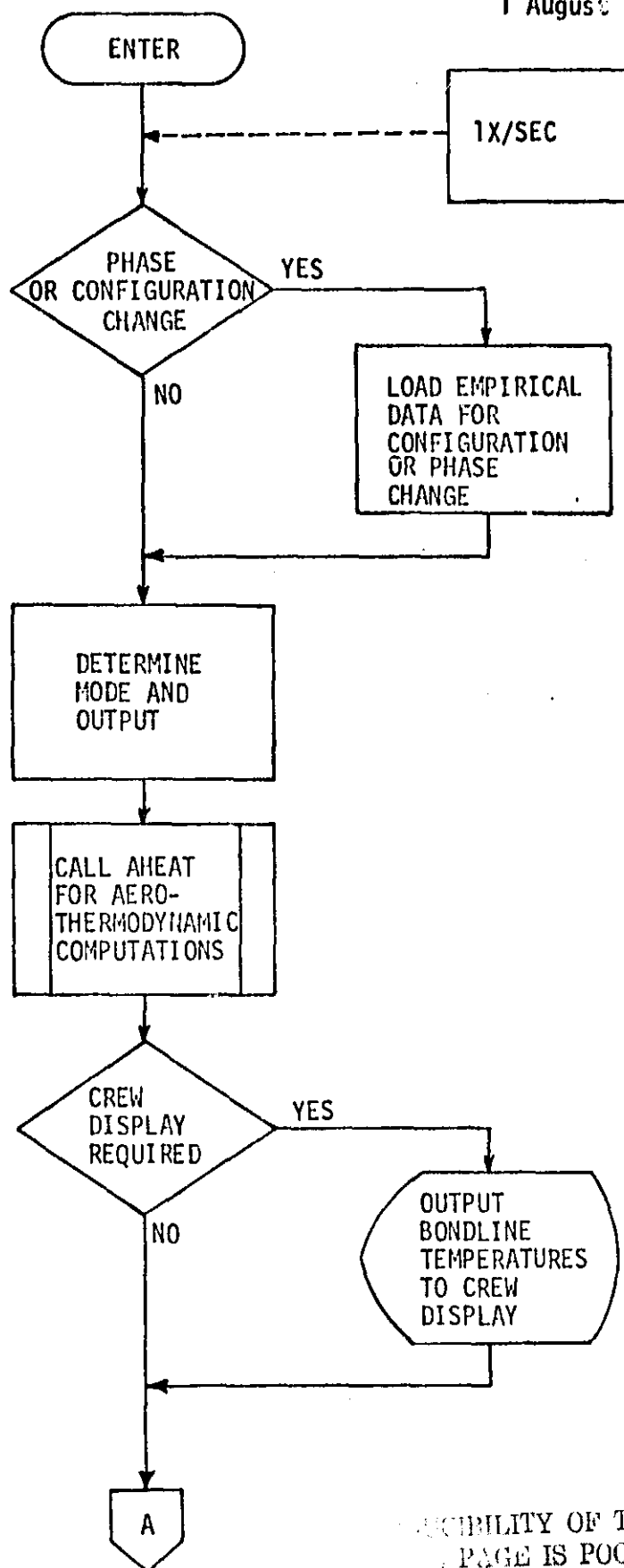
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FIGURE 2-23. AEROTHERMODYNAMICS FLOW DIAGRAM

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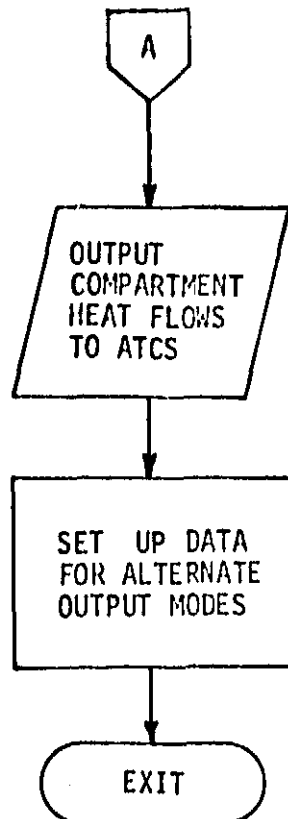


FIGURE 2-23. CONTINUED
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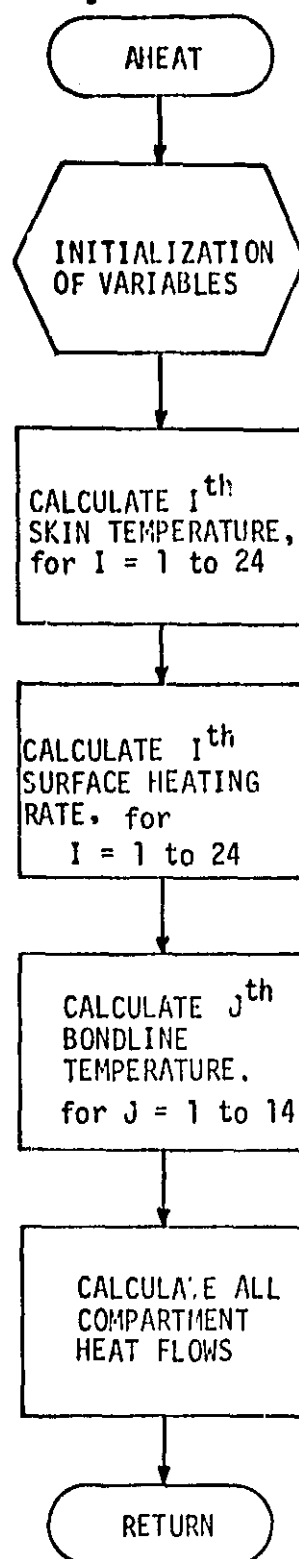


FIGURE 2-24. AHEAT FLOW DIAGRAM
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2.4.2.1 Aerothermodynamic Module Description and Performance Parameters

This module is used during entry and ascent mission phases to evaluate the skin temperature and the conducted heat to the bondline. These results are used in the bondline temperature calculations. Structure temperatures at a total of 181 orbiter locations are recorded during a mission; however, only 14 bondline temperatures are crew monitored and utilized to provide flight dynamics information (Reference 21). These results are considered critical performance parameters for the training simulator. The performance parameters listed in Table 2-10 were selected using the criteria developed in section 2.1.1.

2.4.2.2 Entry Aerothermodynamics Simulation

During portions of the entry mission phase, it is necessary to operate the orbiter near its maximum heat loading to obtain maximum downrange position. A total of 24 surface points will be used in describing the vehicle surface for temperature measurement purposes. For a given angle of attack, α , the surface temperature at a discrete point on the vehicle surface, due to aerodynamic heating can be computed using the equation (Reference 16):

$$T_s = k \rho_a^x V^y$$

ρ_a = atmospheric density

V = vehicle velocity

T_s = Temperature

This relationship is based upon empirically determined values of k , x , and y . These constants can be arrived at through the use of test data and curve fit equations. It has been estimated that, for each point selected on the orbiter surface, values of k , x , and y for 5 V 's and 4 α 's should provide sufficient accuracy. Linear interpolation will be used for points between the tabular values.

The heat flow rate due to aerodynamic heating will be determined through the use of test data in an empirical relationship (Reference 24). The relationship is based upon vehicle velocity, atmospheric density, dynamic pressure, angle of attack, and surface area:

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Table 2-10.
PERFORMANCE PARAMETERS AND COEFFICIENTS

SYMBOL	PARAMETER DESCRIPTION	USE ^a
T_s	Surface Temperatures (24)	P
T_b	Bondline temperatures (14)	CP
\dot{Q}_a	Surface heat rates (24)	P
\dot{Q}_c	Conducted compartment heat rates	P
\dot{Q}_R	Radiative compartment heat rates	P
T_c	Compartment wall temperatures	P
A	Surface area of selected sections (24)	I
B	Bondline temperature measurement locations	I
X	Material thicknesses	I
K_m	Material thermal conductivities	I
ρ_m	Material densities	I
C_m	Material specific heats	I
ϵ	Material emissivities	I
C_r	Constants of black body radiation	I
k,x,y	Surface temperature related empirical constants	I
V	Vehicle velocity	I
q	Vehicle dynamic pressure	I
α	Vehicle angle of attack	I
ρ_a	Atmospheric density	I

a

- P - Performance parameter
 CP - Critical performance parameter
 I - Input

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$$\dot{Q}_a = f(V, \rho_a, q, \alpha, A).$$

Where:

V = vehicle velocity

 \dot{Q}_a = heat transfer rate due to aerodynamic heating ρ_a = atmospheric density

q = dynamic pressure

 α = angle of attack

A = surface area of section

Curve fit equations will be generated using test data to determine \dot{Q}_a . The outer surface of the orbiter will again be divided into 24 sections. A different equation will then be applied to each section to determine \dot{Q}_a .

The temperature at the bondline can now be determined using the surface temperature inputs and heat flow rates due to aerodynamic heating. These temperatures can be found by solving the general heat conduction equation applied to each section, the general form being (Reference 15):

$$\dot{Q}_c = K_m A \Delta T / \Delta x$$

Where:

 \dot{Q}_c = conducted heat transfer rate, per unit of time, due to aerodynamic heating K_m = thermal conductivity of the material

A = area normal to the heat flux

 ΔT = temperature difference between the bondline and vehicle surface Δx = thickness of the material normal to the heat flux

The steady-state temperature at the bondline is then in this case, calculated to be:

$$T_b = T_s - (\dot{Q}_c \Delta x / K_m A)$$

Where:

T_b = bondline temperature

T_s = surface temperature

\dot{Q}_c, K_m, A, X as previously defined

Partial modification of the general equation may be necessary in specific sections to include more than one dimension of heat flow. Provision must also be made to allow for variations in the values of thermal conductivity as it is both temperature and pressure dependent for some materials. The bondline temperature will then be stored for output to crew display, analysis, and/or software module verification.

If those steady-state approximations do not provide acceptable accuracy for training purposes, it will be necessary to numerically solve the general heat conduction equation:

$$\partial T / \partial t = (K_m / \rho_m C_m) (\partial^2 T / \partial x^2)$$

Where:

T = temperature of the material

t = time

K_m = thermal conductivity

ρ_m = material density

C_m = specific heat

x = distance at which the temperature is evaluated

The quantity of heat transferred, due to aerodynamic heating, into other orbiter compartments will be computed in conjunction with compartment wall temperatures to provide inputs to the ATCS module. These parameters may be evaluated by applying an equation similar to the one used in the bondline temperature calculation. This equation will be applied to each layer of material until the compartment walls are reached.

The general, steady-state heat conduction equation for one surface is then:

$$\dot{Q}_c = A \Delta T / \sum_{i=1}^n (\Delta x_i / K_{m_i})$$

for: $i = 1, 2, 3, \dots n$

where: n = number of layers of material

Q_c, A, T, X, K_m as previously defined

The heat rate per unit area radiated from the wall into the compartment is then expressed by the relationship (Reference 15):

$$\dot{Q}_R = \epsilon C_\sigma T_c^4$$

Where:

\dot{Q}_R = heat rate per unit area radiated
into the compartment

ϵ = emissivity

C_σ = constant of black body radiation

T_c = compartment wall temperature

Again, this equation may require modification to allow for multidimensional heat flows and compartment wall interaction. The relationship only describes the radiative contribution of heat to the inner compartment due to aerodynamic heating.

2.4.2.3 Ascent Aerothermodynamics Simulation

The ascent phase aerothermodynamics computations will use the same equations as the entry phase, however, the table structure will differ:

- (a) The ascent tables will require fewer angle of attack points, since the angle of attack varies less during ascent than entry.
- (b) The ascent tables will provide heating coefficients for all three ascent configurations: Orbiter/ET/SRB's, Orbiter/ET, and Orbiter alone.

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Considering the empirical equation for orbiter surface temperature;

$$T_s = k \rho_a^x V^y$$

it is estimated that, for each angle of attack, empirical values of k, x, and y will be needed at 5 V's for each of the discrete surface points of interest. Thus, storage requirements for this table in the ascent, software module would be less than the storage required for the entry phase table.

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2.4.2.4 Aerothermodynamics Module Verification

The simulation module will be driven by a support software routine which will receive inputs to be passed (via common, argument list, and/or block data) to the simulation module. These inputs include parameters such as aerodynamic data tables and flags to indicate the mode in which the module is to be exercised. The driver will also indicate the input/output requirements of the simulation module. These requirements include training simulation (real-time), post simulation analysis, and software module verification. The software module will be exercised at a rate of one execution per second to provide output parameter updates.

Verification of the simulator software module will be accomplished using suitable test data and verification techniques. One suitable means of verification would exist in the construction of a data file containing special check points of known values. The module could then be exercised and the results compared with test and design data. The data points selected as check points would include not only values upon which empirical constants are based, but also points in between for which results are known.

The software module can be exercised with step inputs and special reference trajectories. By holding one particular variable constant, for example heat load, the other parameters can be calculated and compared with off-line computations.

Special reference trajectories to be used in the verification of the software module might be the same as those found in References 17,18 and 19. The trajectory variables would be input to the software module and the module computed results compared with similar results found in the test and design data found in the references. The reference trajectories will simulate all configurations during entry and ascent, thereby exercising all options required for software module verification.

Trajectory tapes generated by other engineering analysis programs (Reference 23) incorporating an aerodynamic heating module may also be used in a verification technique. The same trajectory would be utilized with the simulation module and the engineering analysis program. Their respective results could then be compared. This would require the use of a special driver routine to read and reformat the data tape for use with the simulation module.

For some parameters, off-line calculations might be necessary to evaluate the results in proper perspective as the parameters calculated in each module might not be exactly equivalent, but would be related. Engineering judgement would have to be implemented to determine conversion methods and accuracy criteria for module verification.

2.4.3 Mass Properties

This section describes the Shuttle mass properties simulation software module. Simulation and verification of the Shuttle mass properties module will be required for ascent, on-orbit, and entry mission phases. The software routine will simulate changes in vehicle gross weight, center of mass, and inertia tensors.

A general inertia tensor is conveniently depicted as a symmetric three-by-three matrix, as follows:

$$I = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix}$$

Inputs to the mass properties simulation software include (Reference 16):

- propellant remaining (ME, OMS, etc.)
- mission type
- configuration discretizes
- payload
- mission extension kits if any

The outputs of the mass properties simulation software will consist of:

- vehicle gross weight
- vehicle center of mass location
- vehicle inertia tensor

These output parameters will provide inputs to the vehicle equations of motion (EOM) and/or module verification procedures. The interaction between the mass properties simulation module and other systems simulation modules is shown in Figure 2-25. The performance parameters described in Table 2-11 were selected using the criteria defined in section 2.1.1.

2.4.3.1 Mass Properties: Ascent

In the ascent mission phase, the Shuttle vehicle mass properties will involve the Orbiter plus the solid rocket boosters (SRB) and external tank (ET). The factors having the greatest dynamic influence on mass properties are then (Reference 16):

- solid rocket propellant remaining
- external tank fuel/oxidizer remaining
- OMS fuel/oxidizer remaining
- solid rocket separation
- external tank separation

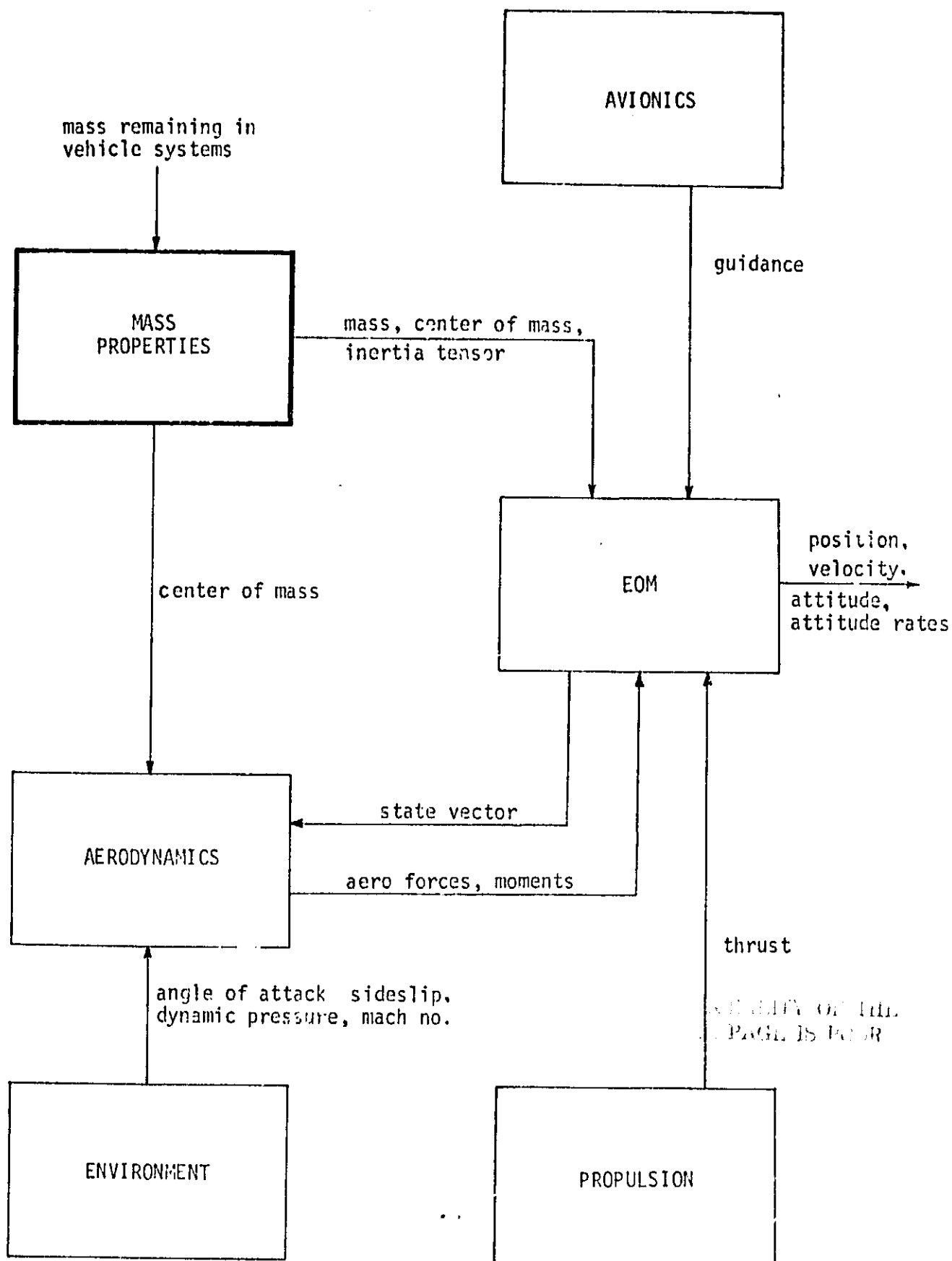


FIGURE 2-25. MODULE INTERFACES
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TABLE 2-11. MASS PROPERTIES MODULE PARAMETERS

PARAMETER DESCRIPTION	TYPE ^a
Orbiter vehicle mass (less fuel/oxidizer)	I
Orbiter vehicle mass center (less fuel/oxidizer)	I
Orbiter vehicle inertia tensor (less fuel/oxidizer)	I
External tank mass (dry)	I
External tank mass center (dry)	I
External tank inertia tensor (dry)	I
SRB mass (empty)	I
SRB mass center (empty)	I
SRB inertia tensor (empty)	I
P/T vehicle mass (less fuel/oxidizer) ^b	I
P/T vehicle mass center (less fuel/oxidizer)	I
P/T vehicle inertia tensor (less fuel/oxidizer)	I
MPS fuel/oxidizer masses	P
MPS fuel/oxidizer mass center	P
MPS fuel/oxidizer inertia tensor	P
SRB propellant mass	P
SRB propellant mass center	P
SRB propellant inertia tensor	P
OMS fuel/oxidizer masses	P
OMS fuel/oxidizer mass center	P
OMS fuel/oxidizer inertia tensor	P
RCS fuel/oxidizer masses	P
RCS fuel/oxidizer mass center	P
RCS fuel/oxidizer inertia tensor	P
P/T fuel/oxidizer masses	P
P/T fuel/oxidizer mass center	P
P/T fuel/oxidizer inertia tensor	P
Shuttle vehicle (total) mass	CP
Shuttle vehicle (total) mass center	CP
Shuttle vehicle (total) inertia tensor	CP

^b P/T denotes payload/target ^aLegend:

P = Performance Parameter

I = Input

CP = Critical Performance Parameter

These inputs will enable the mass properties simulation software to compute outputs based upon information selected from performance data tables composed of:

- ascent configuration
- mass of fuel/oxidizer remaining
- time since SSME and/or SRB ignition
- fuel/oxidizer mass position
- inertia tensors of shuttle component masses

As shown in Figure 2-26 , outputs from the mass properties simulation software will be updated 10 times per second during ascent.

2.4.3.2 Mass Properties: On-Orbit

Orbital insertion initiates the on-orbit phase of the mass properties simulation software. During on-orbit the Orbiter mass properties are affected by:

- RCS fuel/oxidizer remaining
- OMS fuel/oxidizer remaining
- mission type
- payload/target (P/T) interaction

The amount of maneuvering required of the Orbiter during the on-orbit phase will affect the OMS/RCS fuel/oxidizer usage. This will require that updates based upon these parameters be performed dynamically as fuel/oxidizer is consumed. A larger consumption rate will occur during rendezvous or P/T docking/attachment.

Payload/target influences upon the orbiter mass properties are dependent upon:

- P/T type (propulsive or non-propulsive)
- P/T position in the payload bay
- P/T attachment/docking
- P/T rendezvous

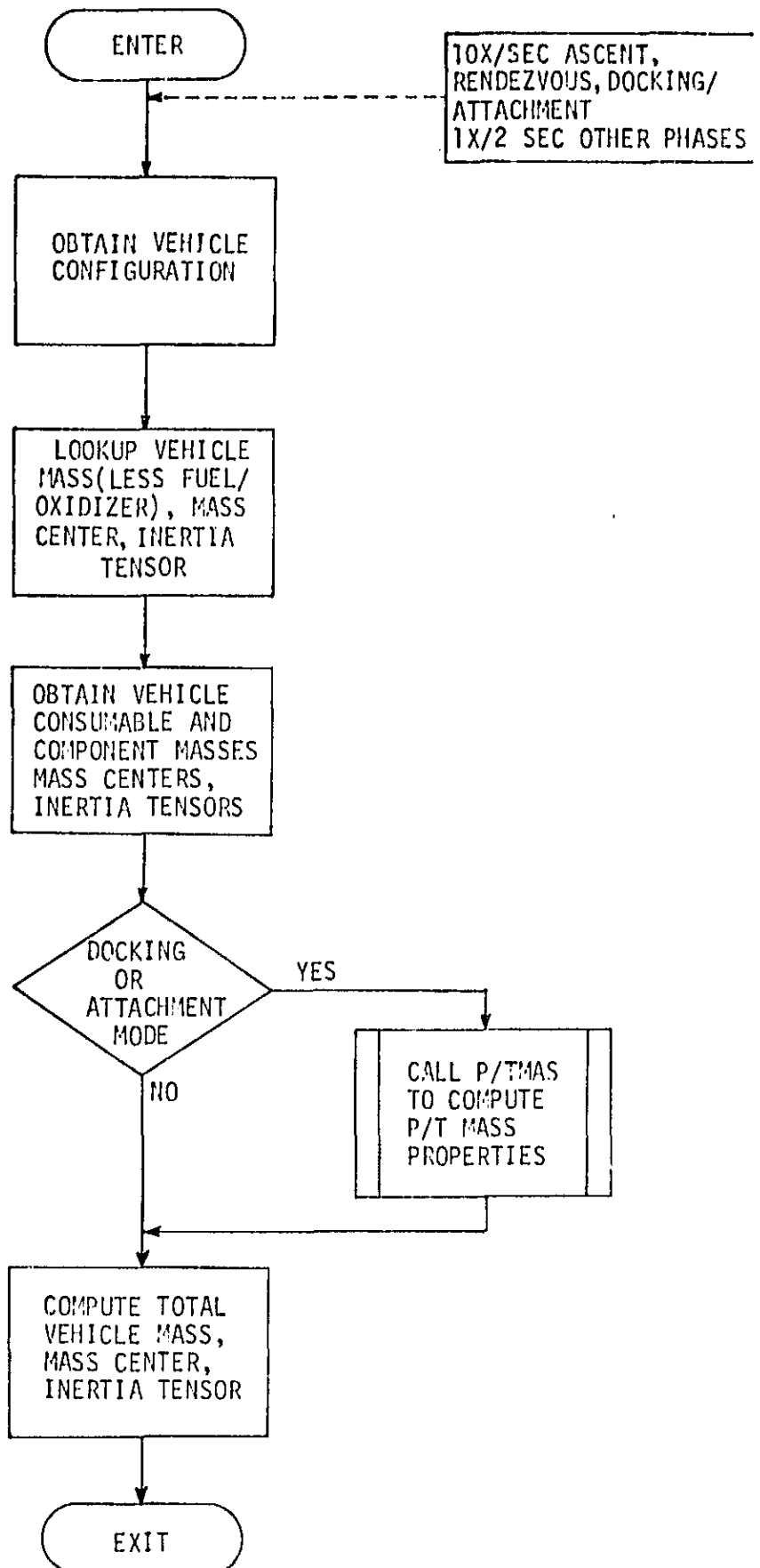


FIGURE 2-26. MASS PROPERTIES FLOW DIAGRAM

An attachment/docking or rendezvous boolean will be used to indicate the respective mode. Attachment/docking or rendezvous necessitates that mass properties updates be made at a rate of 10 times per second as shown in Figure 2-26. Other on-orbit modes require an update of once per 2 seconds (Reference 24).

Upon attachment/docking, the P/T is assumed integral with the Orbiter. Its mass properties must then be computed and combined with those of the Orbiter. Figure 2-27 shows the P/T mass properties flow diagram.

The orientation of the P/T will influence its contribution to the Orbiter mass properties during attachment/docking. The P/T inertia tensor must be first rotated to an Orbiter parallel axis as follows (Reference 25):

$$I_{op} = R I_{P/T} R^T$$

Where: I_{op} = P/T inertia tensor in an orbiter parallel axis

$I_{P/T}$ = P/T inertia tensor about P/T axis through its mass center (C.M.)

R = rotation matrix

The parallel axis theorem can now be employed to transform the P/T inertia tensor to a P/T inertia tensor about the Orbiter centered axes. Applying the parallel axis theorem from Reference 26 :

$$I_{oc} = I_{P/T} + M_{P/T} D^2$$

Where:

I_{oc} = inertia tensor component of the P/T about the orbiter centered axes

$I_{P/T}$ = as previously defined

M = mass of the P/T

D = perpendicular distance from Orbiter inertia tensor axis to $I_{P/T}$ tensor axis

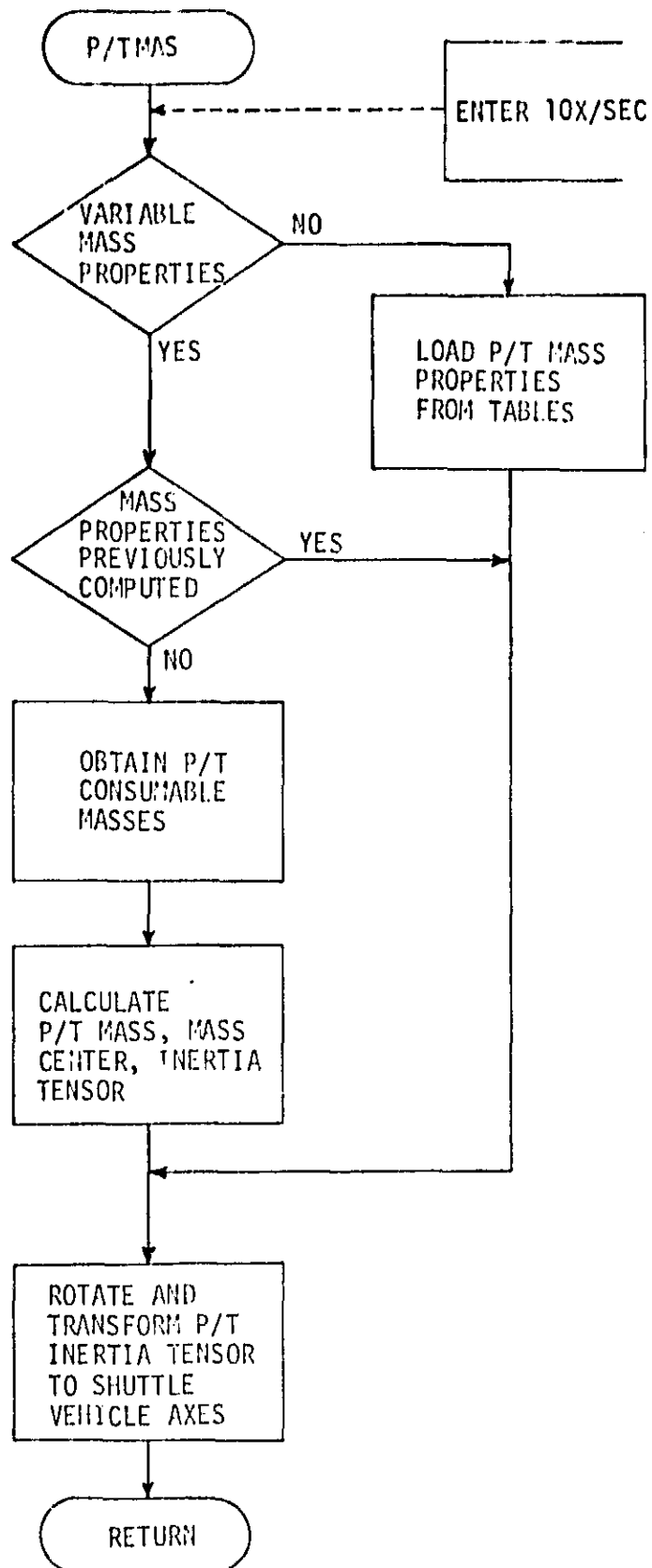


FIGURE 2-27. PAYLOAD/TARGET MASS PROPERTIES FLOW DIAGRAM

The P/T inertia tensor can now be combined with the orbiter vehicle inertia tensor about the corresponding axis.

2.4.3.3 Mass Properties: Entry and Aeroflight

Mass properties during the entry and aeroflight phases are dependent upon the following:

- payload type
- payload position in payload bay
- OMS fuel/oxidizer residuals
- RCS fuel/oxidizer remaining

Payload mass properties will be constant and non-updating during this phase. The overall mass properties variations during this phase will be small. These variations will be based upon the amount of OMS/RCS fuel/oxidizer consumed during de-orbit burn and attitude control in entry.

The aeroflight phase uses small amounts of RCS thrusting for yaw control. The minor changes in mass properties occurring in the entry and aeroflight phases require the mass properties simulation software module to provide updates at a rate of once per 2 seconds.

2.4.3.4 Module Verification

Verification of the Shuttle mass properties simulation software can be accomplished through the use of various techniques. One method of verification would utilize specialized input data points in a reference file. This data would provide fixed amounts of fuel/oxidizer remaining for all mission phases and vehicle configurations. The Shuttle mass properties parameters could then be evaluated with this data using the simulation module and the results checked with off-line calculations. Suitable accuracy criteria, developed using engineering judgement and test data, would provide validation standards.

Another verification technique can be implemented using other engineering analysis programs as described in Reference 23. The same data could be input to the engineering analysis program and the simulation software module. Their results would then be compared. This method might be more difficult to implement than that previously discussed since the test data would have to be constructed for input to both programs.

2.5 VEHICLE DYNAMICS MODULES

This section briefly describes the Shuttle vehicle dynamics simulation modules and their interfaces with other simulation modules. Validation methods, and data sources are also discussed. References 24 and 27 provided much of the basic information for this section.

Table 2-12 shows the hierarchy of simulation modules under the Vehicle Dynamics category. Mechanical subsystems per se (v.1.1.n) will be discussed in detail in a later report. This report is concerned only with the vehicle dynamic aspects of mechanical subsystems: i. e., the reaction forces and moments which they exert upon the Shuttle vehicle.

Figure 2-28 provides an overview of the interfaces among the simulation modules involved in vehicle dynamics. The translational and rotational equations of motion (EOM) modules use force and moment, mass and inertia inputs to compute vehicle state variables, both absolute (Shuttle vehicle) and relative (multiple-body). Forces and moments come from gravity, aerodynamics, propulsion, venting, and mechanical-subsystem modules; mass, inertias, and c.g. position are provided by the mass-properties module. Bending and slosh dynamics produce additional body forces and moments; they also affect the apparent angles, rates and accelerations sensed by the avionics. Finally, the avionics modules provide commands to propulsive systems and control actuators, while power subsystems modules provide any required electrical and hydraulic power.

Simulator hardware interfaces of interest, not shown on this figure, include the visual and motion systems, which are driven by translational and rotational dynamics, and the instructor/operator station, which allows insertion of simulated faults into vehicle subsystems simulation modules.

Table 2-13 provides an integrated list of parameters for all vehicle dynamics simulation modules.

TABLE 2-12. VEHICLE DYNAMICS (V.3) SIMULATION MODULE HIERARCHY

V.3.1	RIGID-BODY EQUATIONS OF MOTION
V.3.1.1	Translational EOM
V.3.1.2	Rotational EOM
V.3.1.3	Multiple-Body EOM
V.3.2	MECHANICAL-SYSTEM DYNAMICS
V.3.2.1	Landing/Deceleration Dynamics
V.3.2.1.1	Landing Gear
V.3.2.1.2	Drag Parachute
V.3.2.2	Docking Dynamics
V.3.2.3	Separation Dynamics
V.3.2.3.1	ET/SRB Separation
V.3.2.3.2	Orbiter/ET Separation
V.3.2.4	Actuation-Mechanism Dynamics
V.3.2.5	Payload Deployment/Retrieval Dynamics
V.3.3	BENDING & SLOSH DYNAMICS
V.3.3.1	Body Bending Dynamics
V.3.3.2	Fuel SLOSH Dynamics

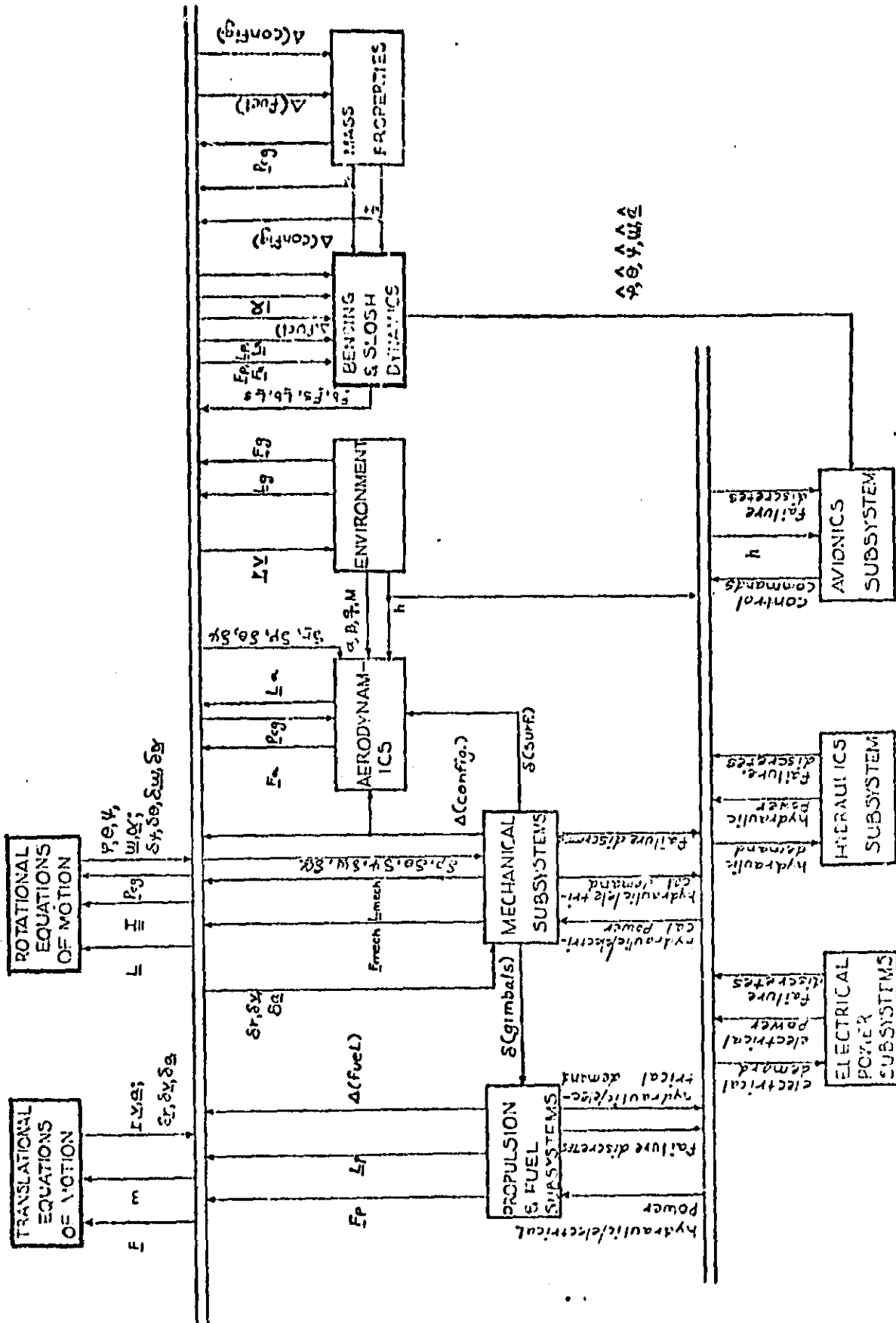


FIGURE 2-28. OVERVIEW OF DYNAMICS MODULE INTERFACES. (DATA TRANSFER IS NORMALLY VIA COMMON STORAGE, WHETHER SHOWN DIRECT OR BUSSED ON THIS FIGURE.)

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TABLE 2-13. VEHICLE DYNAMICS SIMULATION PARAMETERS

SYMBOL	DESCRIPTION	TYPE ^a
F_g	gravitational force, in ECI axes	I
F_{mech}	mechanical-system reaction forces in body axes	I
F_a	aerodynamic force, in body axes	I
F_p	propulsive forces, in body axes	I
F_v	venting forces, in body axes	I
L_g	gravity-gradient moment, in body axes	I
L_{mech}	mechanical-system reaction moments, in body axes	I
L_a	aerodynamic moment, in body axes	I
L_p	propulsive moments, in body axes	I

TABLE 2-13. (continued)

SYMBOL	DESCRIPTION	TYPE ^a
L_v	venting moments, in body axes	I
M	vehicle mass	I
M_t, M_p	target, payload mass	I
I	vehicle inertia tensor, in body axes	I
I_t, I_p	target, payload inertia tensor	I
P_{cg}	center-of-gravity position in body axes	I
r, v, a	vehicle position, velocity and acceleration vectors	CP
$\delta r, \delta v, \delta a$	two-body relative position, velocity, and acceleration vectors	CP
-	vehicle direction cosines	P
-	vehicle quaternion parameters	P
ϕ, θ, ψ	vehicle euler angles	CP
ω, α	vehicle angular rate and angular acceleration vectors	P
$\delta\phi, \delta\theta, \delta\psi$	two-body relative euler angles	CP
$\delta\omega, \delta\alpha$	two-body relative angular rate and acceleration vectors	P

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SYMBOL	DESCRIPTION	TYPE ^a
$\Delta(\text{config})$	configuration-change	I
	flags (Orbiter/ET/SRB's, Orbiter/ET, Orbiter)	I
$\Delta(\text{fuel})$	fuel consumed (ME and OMS)	I
S_i, ω_i	damping and frequency for bending & slosh modes	I
Q_i	generalized forces for bending & slosh equations	P
q_i	generalized coordinates (normal modes) for bending & slosh	P
$\phi_i(x)$	bending & slosh sensitivity functions (mode shapes); functions of longitudinal position	I
F_b, F_s	bending & slosh forces, in body axes	CP
L_b, L_s	bending & slosh moments, in body axes	CP
$\hat{\phi}, \hat{\theta}, \hat{\psi}$	apparent euler angles at nav base	CP
$\hat{\omega}$	apparent body-axis angular rates at rate-gyro locations	CP
\hat{a}	apparent body-axis sensed accelerations at accelerometer locations	CP

^aLegend: I = input

P = performance parameter

CP = critical performance parameter

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2.5.1 Rigid-Body Equations of Motion

These modules compute Orbiter vehicle translational and rotational state variables during all mission phases. During certain mission phases, equations of motion must simultaneously be solved for one or more bodies other than the Orbiter: Boeing 747 launch aircraft, separated SRB's or ET, rendezvous and docking targets, and payloads being deployed or retrieved by means of the Payload Deployment and Retrieval Subsystem (PDRS).

2.5.1.1 Translational EOM

Shuttle missions span several dynamical regimes, requiring different implementations of translational EOM. Table 2-14 briefly summarizes the modes of operation appropriate to each mission phase. Note that the Coordinate System(s) entry refers only to the coordinates in which the EOM are solved; a variety of other coordinate sets will also be in use for generation of auxiliary variables. Under Gravity Model, we do not attempt to specify which spherical harmonics will be used, nor how many, because the references are not in agreement on this point. Entries under Other Major Forces are selective, rather than exhaustive; e.g., additional on-orbit forces include atmospheric drag, RCS burns, and consumables venting. Finally, the two major EOM Formulations to be used are Cowell's Method (direct integration of all vehicle accelerations) and Encke's Method (integration of linear perturbations about a Kepler reference trajectory). Minor variations of these two basic methods will also be used during various mission phases.

2.5.1.2 Rotational EOM

Unlike translational EOM, rotational EOM are implemented in essentially the same manner for all mission phases, although not necessarily at the same iteration rate. The inertia tensor and all external moments will be expressed in body axes. Angular accelerations will be integrated in either direction-cosine or quaternion form (again, the references disagree); Euler angles and direction-cosine matrices will be available for use in other routines.

Table 2-14. IMPLEMENTATION OF TRANSLATIONAL EOM DURING VARIOUS MISSION PHASES.

MISSION PHASE	COORDINATE SYSTEM (S)	GRAVITY MODEL	OTHER MAJOR FORCES	EOM FORMULATION(S)
Prelaunch	ECI (Earth-Centered Inertial)	uniform	Main propulsion, hold-downs.	None; earth-rotation kinematics only.
Ascent	ECI	central force field plus harmonics	Main propulsion, aero	Cowell
On-Orbit	ECI; relative coords for rendezvous	central plus harmonics	O/S burns, docking mechanisms, payload manipulator reactions.	Encke during coast, Cowell during O/S burns.
Entry	ECI	central plus harmonics	aero	Cowell
Aeroflight	ECI	central	aero; ABE propulsion (if any)	Cowell
Final Approach	flat-earth NED (North-East-Down from an earth-fixed point)	uniform (flat-earth)	aero, ABE propulsion, landing gear	Cowell

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2.5.1.3 Multiple-Body EOM

Multiple-body dynamical simulation is required at times during ascent, aeroflight, and on-orbit operations. During on-orbit operations, simulation of near-, mid-, and far-distance regimes may be required. In the ascent and aeroflight phases, we do not anticipate multiple-body simulation requirements beyond the near-distance regime. Multiple-body computation will presumably be terminated when the separating object (ET, SRB or launch aircraft) has departed from a predetermined "sphere of influence" centered on the Shuttle vehicle, beyond which recontact is considered highly unlikely. For completeness, however, Table 2-15 indicates the computational modes appropriate to all combinations of distance regime and mission phase.

Provisions must be made for designating either the target or the Orbiter as the origin of the relative coordinate system for simulation of rendezvous maneuvers in the mid-distance regime.

In the near regime, the Orbiter and other bodies may interact through the medium of various Orbiter mechanical systems -- separation mechanisms, docking mechanisms, PDRS -- as discussed in section 2.5.2. Relative position and attitude variables will be used, in combination with simplified representations of the Orbiter and other-body geometry, to test for undesired contact between the Orbiter and the other body.

2.5.2 Mechanical-System Dynamics

We assume that each mechanical system listed in Table 2-12 will be simulated by an individual software module. Each such module will accept activation commands from the avionics and/or crew station, malfunction discretes from the instructor/operator station, and simulated electrical and/or hydraulic power from appropriate power supply and distribution modules. Internally, the simulation fidelity of these modules will vary from one simulator to another. Some mechanical activities may be simulated as instantaneous actions, simple lags, or approximate transfer functions. Other systems may be simulated in high fidelity, with motors, valves, springs, dampers or whatever all represented as accurately as possible. These details will be discussed in later reports.

Table 2-15 . COMPUTATIONAL MODES FOR MULTIPLE-BODY EOM

DISTANCE REGIME	ON-ORBIT	ASCENT AND AEROFLIGHT
Far	Independent (Cowell or Encke)	Independent (Cowell)
Mid	Relative (Encke or Clohessy- Wiltshire)	Independent (Cowell)
Near	Relative (Gravity-gradient or uniform gravity)	Relative (Cowell)

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For this report, we are only concerned with the interactions between the mechanical-system modules and the vehicle translational and rotational dynamics -- i.e., their reaction forces and moments on the Orbiter vehicle. These forces and moments will be provided in body axes, which requires each mechanical-system simulation module to have access to body-axis geometry data: the direction cosines of the line of action of each reaction force, the point of application (where the mechanical system attaches to the Orbiter structure), and the current c.g. position.

The discussion below briefly discusses the dynamical aspects of each subsystem of interest, using much-simplified figures for clarity.

2.5.2.1 Landing/Deceleration Dynamics

Landing Gear (LG)

Landing gear drop (free-fall) produces a change in aerodynamics, but no perceptible forces or moments.

Initial ground contact will occur with struts fully extended. As indicated by Figure 2-29, vehicle altitude, attitude and geometry will determine which point on the Orbiter (hopefully one of the main landing gear) will contact the ground first; this will determine the instantaneous sign of the pitch and roll moments (from the impact) and the yaw moment (from tire/runway friction). The magnitude of the forces and moments will depend upon the Orbiter rates and accelerations, the simulated spring/damper characteristics of the LG, and the tire/runway friction coefficients. As the Orbiter bounces and/or settles onto all gears, strut dynamics, vehicle dynamics and aerodynamics will intimately interact.

Main-gear braking, Fig. 2-30, will produce retarding forces and pitchdown moments; differential braking and nose-gear steering will produce yaw moments. Tire/runway characteristics used to generate these forces and moments will probably be provided in table lookup or simplified functional form; e. g., NLG steering side force varies roughly as the sine of the tire slip angle.

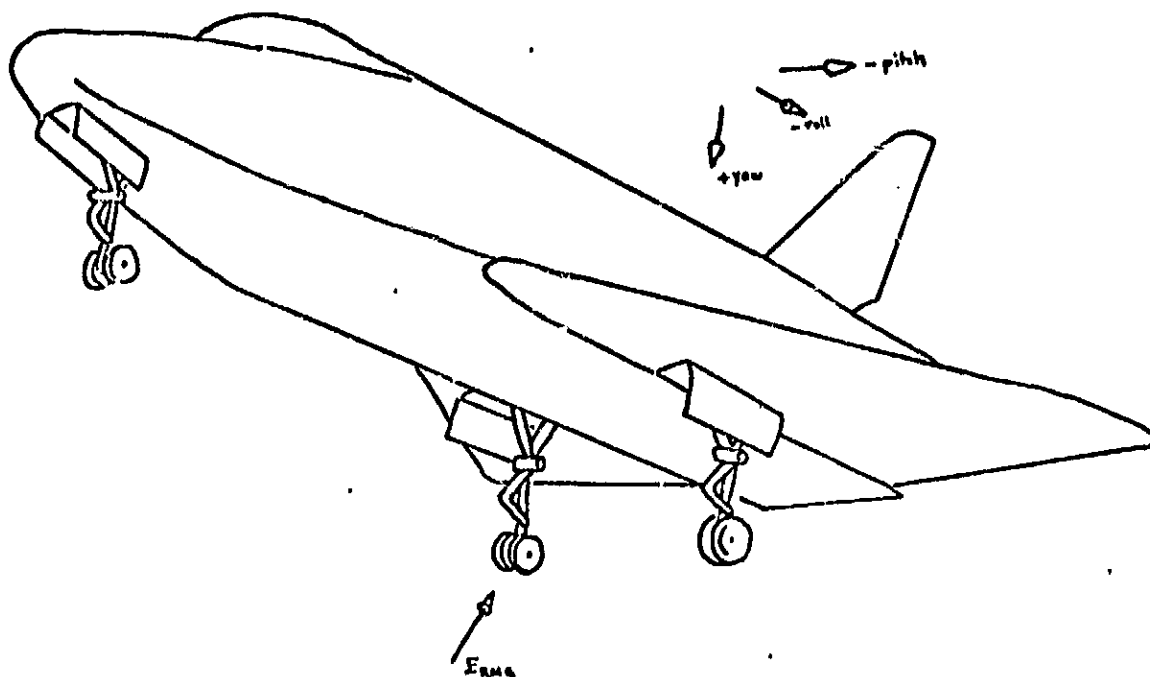


FIGURE 2-29 . EXAMPLE REACTION FORCES AND MOMENTS FROM INITIAL GROUND CONTACT OF RIGHT MAIN LANDING GEAR.

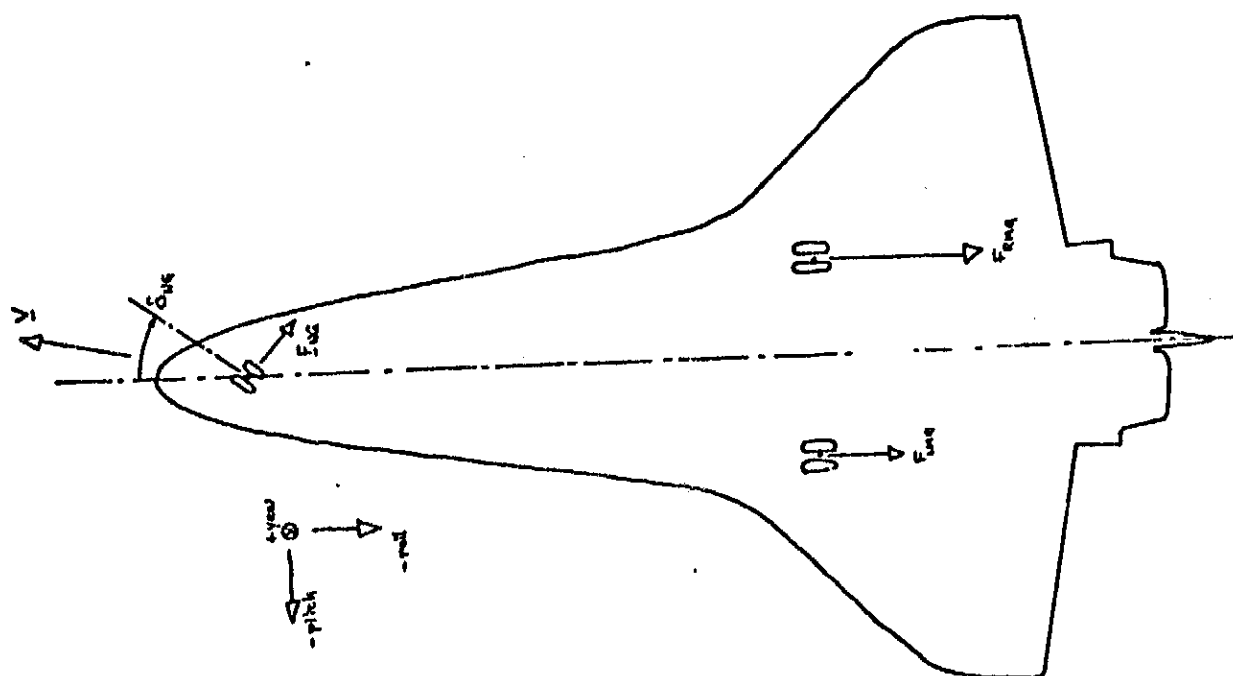


FIGURE 2-30 . EXAMPLE REACTION FORCES AND MOMENTS FROM NOSEWHEEL STEERING AND MAIN-GEAR BRAKING (ORBITER SEEN FROM ABOVE).

Drag Chute

We assume that drag chute dynamics will not be modelled explicitly; rather, the chute-deployment flag will simply cause a change in vehicle aerodynamics.

2.5.2.2 Docking Dynamics

Docking simulation (see Fig. 2-31) is much similar to landing-gear ground contact simulation. Force and moment reactions will depend upon relative translational and rotational states, rates and Shuttle and target masses and inertias, accelerations, as well as spring/damper response. Bounce-off and undesired Orbiter/target contact are possible, and the simulation may include enough detail to faithfully reproduce these phenomena. Alternatively, engineering analysis data may be used to define table-lookup regions of relative states and rates corresponding to successful and unsuccessful docking. When hard-dock is accomplished, the Orbiter and target will be merged into a single vehicle, as regards state variables, mass properties and aerodynamics.

Undocking forces and moments are assumed negligible at present.

2.5.2.3 Separation Dynamics

The nominal operations of the mechanisms for SRB/ET, Orbiter/ET, and Orbiter/launch-aircraft separation do not induce any perceptible reaction forces or moments. Aerodynamic and mass properties changes will be updated for each configuration change, and propulsive systems activities will be simulated where appropriate (SRB separation rockets, Orbiter RCS maneuver following tank separation). We do not consider simulation of separation-system failures in this study.

2.5.2.4 Actuation-Mechanism Dynamics

Reaction forces from actuation of the payload bay door, other Orbiter hatches, etc. are negligible. Control actuators (ME and OMS gimbals, aerosurfaces and body flap) induce changes in body forces and moments by interaction with propulsion and aerodynamic simulations.

2.5.2.5 Payload Deployment/Retrieval Dynamics

The PDRS (manipulator arms), Fig. 2-32 , may be used to assist in docking maneuvers, as well as in the handling of payloads. Reaction forces and moments on the Orbiter and payload/target will depend upon the Orbiter and payload masses and inertias, relative states and rates, the orientation of the various segments of the arms, and the forces and torques applied by each manipulator-arm actuator. These dynamics are inherently complex, and not amenable to simplification. Tests for undesired contact will also be required.

2.5.3 Bending and Slosh Dynamics

Body bending and fuel slosh dynamics will be modelled only during the ascent and entry phases, the entry implementation being much simplified. Body bending modes are excited by aerodynamics and thrust-vector-control inputs. Fuel slosh modes are excited by inertial coupling with rigid-body motions in the pitch and yaw planes. Module outputs include forces and moments due to exchange of momentum between rigid-body dynamics and bending/slosh modes, and contributions to inertial sensor outputs (euler angles, angular rates, and linear accelerations), varying with the sensor longitudinal position.

Extensive offline precomputation will be used to generate a set of simple second-order equations in a set of generalized coordinates -- the "normal modes" of body bending and fuel slosh. Coefficients of these modal equations will be called from storage for each change in vehicle configuration -- SRB and ET separation -- and will vary parametrically with propellant depletion. The modal equations will be integrated in real time; the outputs of the modal equations will then be multiplied by precomputed "sensitivity" (mode shape) functions to generate the perceived effects.

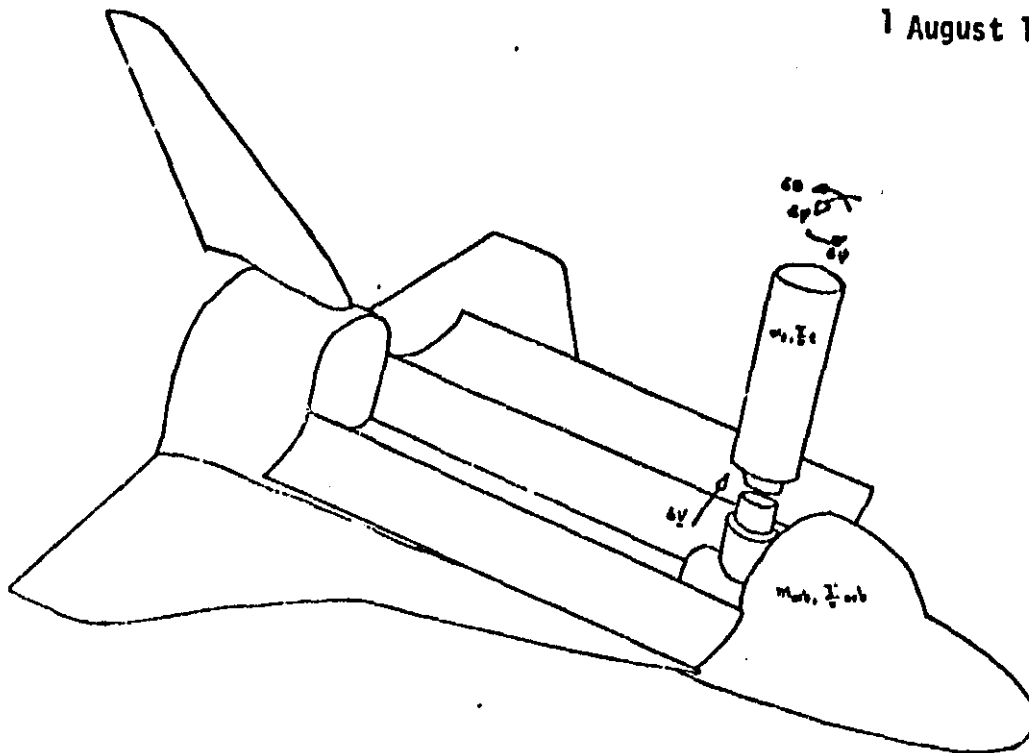


FIGURE 2-31 . ORBITER/DOCKING-TARGET PRECONTACT CONDITIONS.

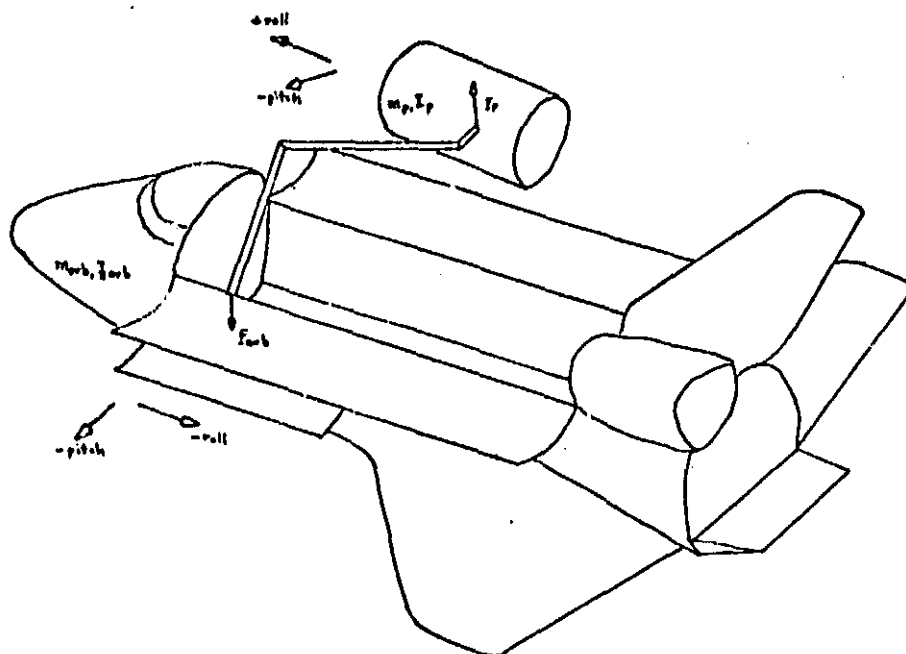


FIGURE 2-32 . EXAMPLE REACTION FORCES AND MOMENTS FROM PAYLOAD DEPLOYMENT.

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2.5.4 Validation Methods and Data Sources

Validation of dynamical simulations by comparison to an existing, previously-validated simulation is a very common approach. Indeed, when a full range of system complexities is included, hand-computation of check data is not feasible, analytical solutions do not exist, and comparison with another powerful simulation is the only available approach.

Programs of adequate accuracy and versatility are currently available and in regular use at JSC (Refs. 28 and 29), both for single-body and multiple-body relative dynamics. Any of the common reference missions should serve as a suitable check case. Reference 23 identifies a number of other simulations covering various aspects of vehicle dynamics. Some care must be applied, in using any of these models as a source of reference data, that

- (a) it is itself adequately validated, and
- (b) is independent of the simulation module validated.

For translational EOM, method of independent validation which is suitable for desk calculation is to remove all perturbing forces, and verify that the simulation module generates the proper Kepler orbit for several sets of initial conditions. Then re-introduce perturbation terms (oblateness, drag, luni-solar forces, etc.) individually, and check the resultant effect against standard closed-form approximations (e. g., of the type given in Ref. 30).

Simple check cases useful for partial validation of rotational EOM include free rotation about any principal axis. Free rotation about an axis other than a principal axis is complex in form, but one simple check is to ensure that angular momentum and rotational kinetic energy are both conserved. Forced rotational motion can be approximately validated by determining the angular-momentum changes resulting from torque pulses of short duration, applied in a variety of body-axis orientations.

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Appropriate force and torque pulses at appropriate body-axis locations can be used to verify proper handling of inputs from mechanical-system modules, in advance of integrated validation of mechanical-system and vehicle-dynamics modules. On-line graphics capability would be desirable for verifying proper operation of the computations and logic involved in detecting undesired contact between the Orbiter and other bodies involved in multiple-body dynamical simulation. Reference 31 describes a JSC software package of potential utility for this application.

SECTION 3
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